A Review of Short-Baseline Decay-in-Flight Experiments

Intensity Frontier Neutrino Subgroup Workshop

6-7 March 2013, SLAC

David Schmitz, University of Chicago

Some Things I Won't Discuss

- This is a talk about addressing existing anomalies (including from short-baseline DIF experiments) that point to the possible existence of **sterile neutrinos**, **not** about other physics being explored over short baselines with decay-in-flight neutrino beams:
  - Cross Sections on Nucleons, Free and in Nuclei (C. Mariani)
  - Nuclear Effects, Theory and Experimental Input (U. Mosel)
  - Monte Carlo Cross Section Model Comparisons (H. Gallagher)
  - MicroBooNE and LAr Cross Section Measurements (O. Palamara)
  - Flux, Cross Section, Nuclear Effects, Scattering Experimental Systematics (J. Morfin)
  - Neutrino Scattering Systematics and CP Violation Measurements (P. Coloma)
  - Need for a Near Detector (P. Vahle)

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  - ~~Need for a Near Detector (P. Vahle)~~

actually, it is about that one…

More Things I Won't Discuss

- The existing anomalies

- No time and no need, they are familiar to us by now and many talks at this workshop have discussed the hints or strategies for new searches
  - Review of Current State of Sterile Neutrino Data (B. Louis)
  - Review of Radioactive Source Sterile Searches (J. Link)
  - Review of Decay-at-Rest Sterile Searches (L. Winslow)
  - Sterile Searches with Atmospheric Neutrinos (F. Halzen)
  - Sterile Neutrinos in Supernova Environments (G. Fuller)
  - Short-Baseline Experiments with Reactors (E. Blucher)
  - Also, "Light Sterile Neutrinos: A White Paper" (arXiv:1204.5379)

Suffice it to say, the HEP community strongly desires a satisfactory resolution to this puzzle through

a set of definitive experiments!

A Multi-Faceted Approach

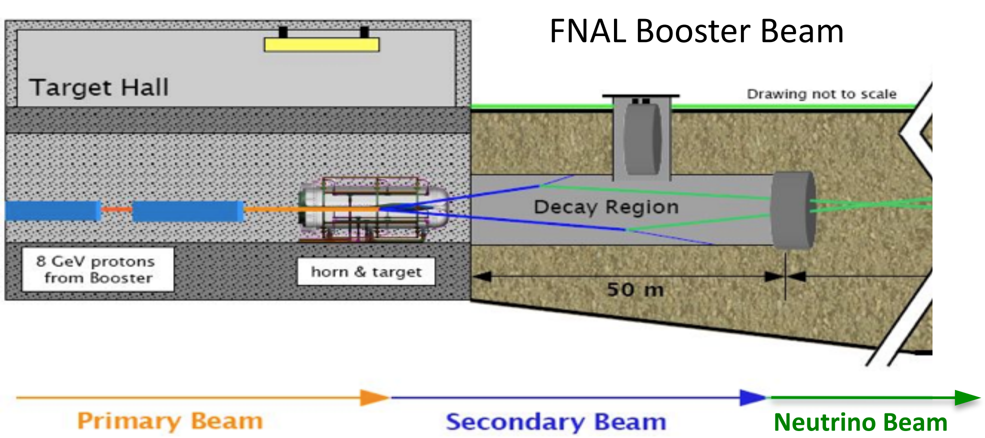
- *"Given the potential implications of sterile neutrinos, it is important to confirm their existence in multiple (preferably orthogonal) approaches."* Light Sterile Neutrinos: A White Paper (arXiv:1204.5379)

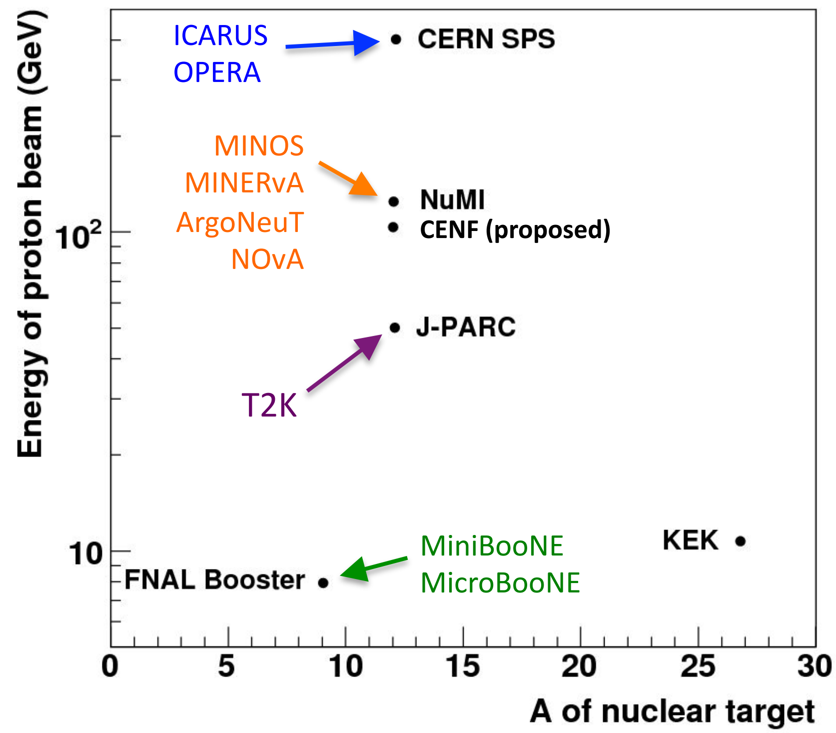
Radioactive neutrino sources	$\nu_e/\bar{\nu}_e$ dis.	100s of keV, 10s of cm
Nuclear reactor antineutrinos	$\bar{\nu}_e$ dis.	< 10 MeV, < 20 m
Stopped π beams	$\bar{\nu}_\mu \to \bar{\nu}_e$	~ 30 MeV, 30 m
Stopped K beams	$\nu_\mu \to \nu_e$	235.5 MeV, 160 m
Decay in flight π/K beams	$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu/\bar{\nu}_\mu$ dis. , $\nu_e/\bar{\nu}_e$ dis.	500 MeV – 2 GeV 100 m – 2000 m
Atmospheric neutrinos	$\nu_\mu/\bar{\nu}_\mu$ dis.	< 20 GeV, 15 – 130 km 100 GeV – 400 TeV, $< 1.3 \times 10^4$ km
Cosmology	indirect N_s, m_ν	

Finally, What I Will Discuss…

- Why Decay-in-Flight
- Examine the existing anomaly for guidance
- Review current proposals
  - Submitted White Papers + a CERN proposal

The Basic DIF Neutrino Beam





Relevant features of all DIF ν beams:

1. $\nu_\mu(\bar{\nu}_\mu)$ flavor beam to first order
2. always some (order 1%) $\nu_e(\bar{\nu}_e)$
3. "wrong sign" content not negligible (especially in antineutrino mode)
4. on-axis beam will span ν energies, mean increases some with proton energy
5. notoriously difficult to know fluxes with high precision

A definitive π decay-in-flight based experiment is an important component of a program to answer the sterile neutrino question

1. DIF beam provides a rich oscillations program with a single facility:
   - $\nu_\mu \rightarrow \nu_e$ appearance
   - ν_μ and ν_e disappearance
   - both neutrinos and antineutrinos
   - CC and NC interactions

2. Anomalies exist here and these need to be addressed

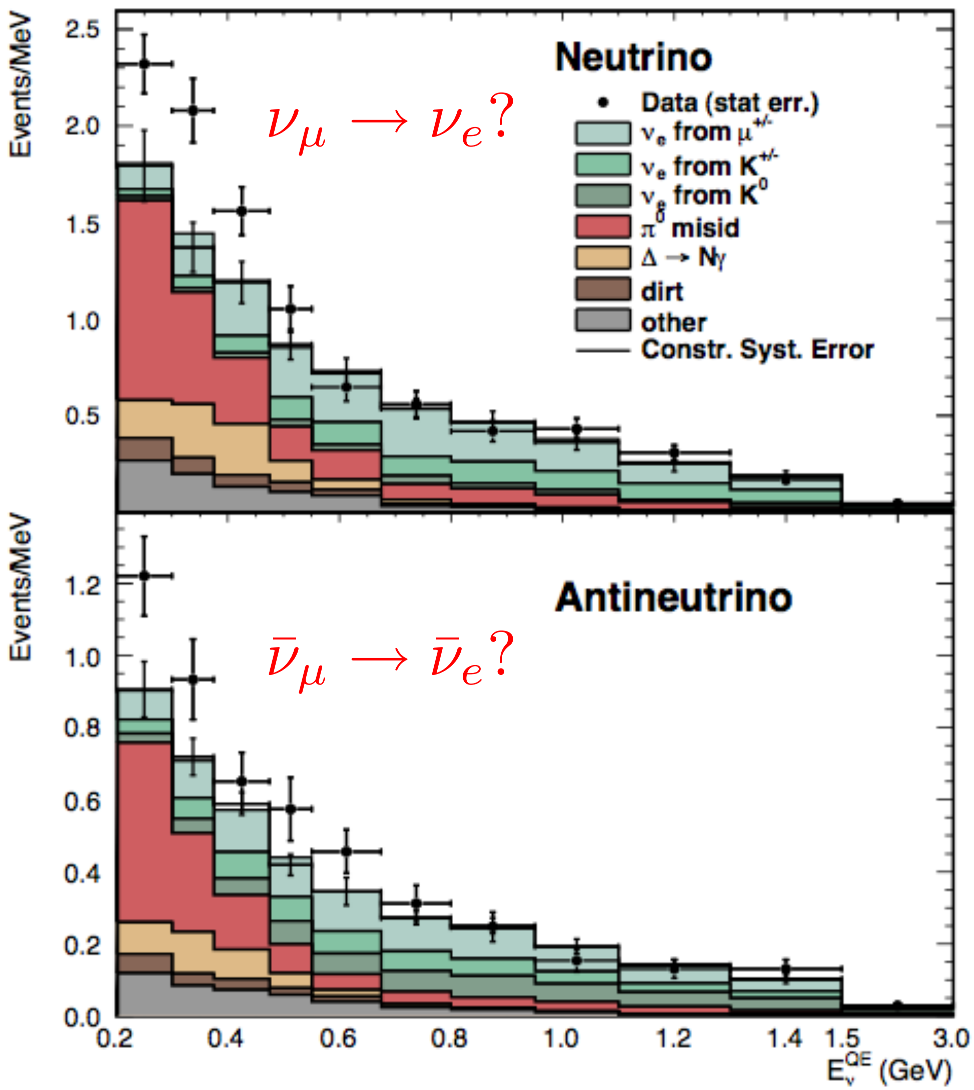
3. Can (in some cases) leverage existing facilities (beams and detectors)

4. Can (in all cases) learn from experiences of past DIF efforts

5. DIF beams over short-baseline allows modest detector sizes which, in some cases, can serve as a prototype for larger detectors of the same technology needed for long-baseline physics*

*a fringe benefit of sorts

The Existing DIF Anomaly



<u>MiniBooNE Final Results:</u>

3.4σ excess in neutrino mode

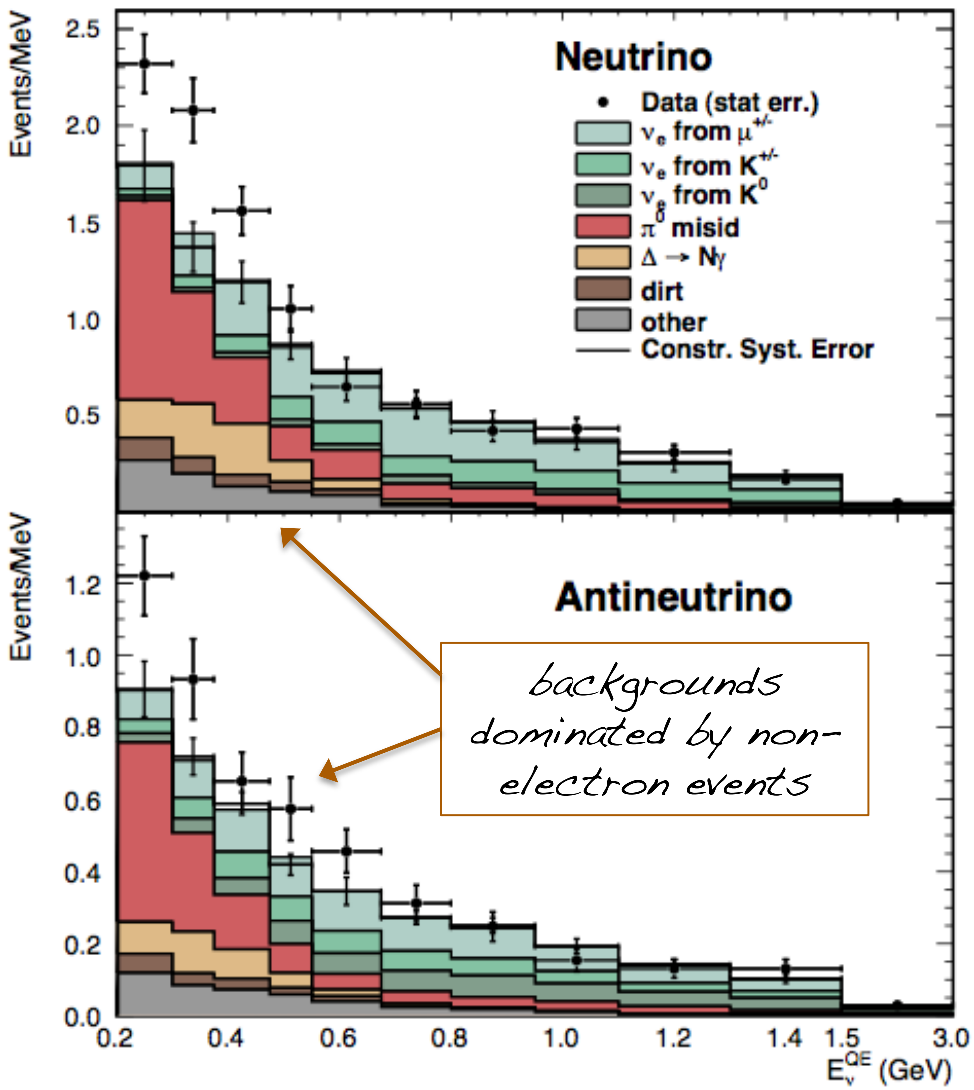
$$162.0 \pm 28.1(\text{stat}) \pm 38.7(\text{syst})$$

2.8σ excess in antineutrino mode

$$78.4 \pm 20.0(\text{stat}) \pm 20.3(\text{syst})$$

arXiv:1207.4809

The Existing DIF Anomaly



MiniBooNE Final Results:

3.4σ excess in neutrino mode

$$162.0 \pm 28.1(\mathrm{stat}) \pm 38.7(\mathrm{syst})$$

almost 6σ statistical result, systematics limited

2.8σ excess in antineutrino mode

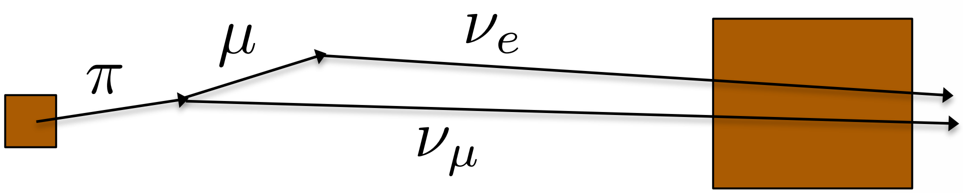
$$78.4 \pm 20.0(\mathrm{stat}) \pm 20.3(\mathrm{syst})$$

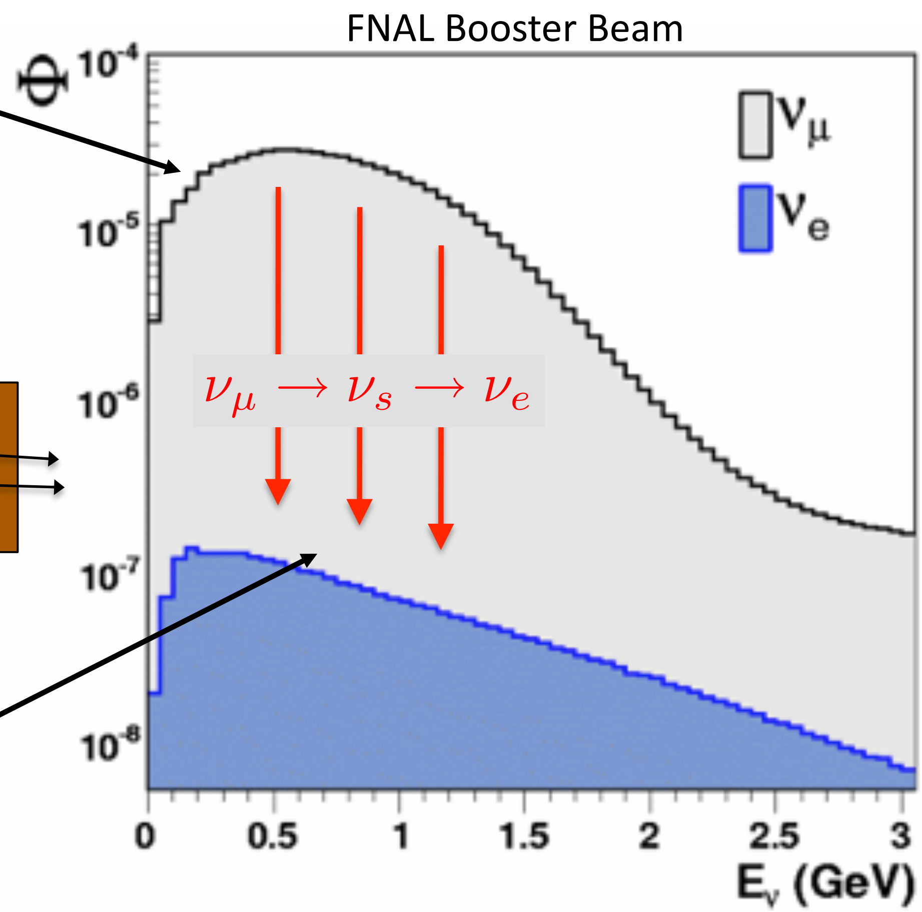
almost 4σ statistical result

arXiv:1207.4809

The One Detector Analysis

effectively unoscillated large-statistics muon neutrino CC sample provides a <u>constraint</u> on (*flux × xsec*) of electron neutrino CC rate

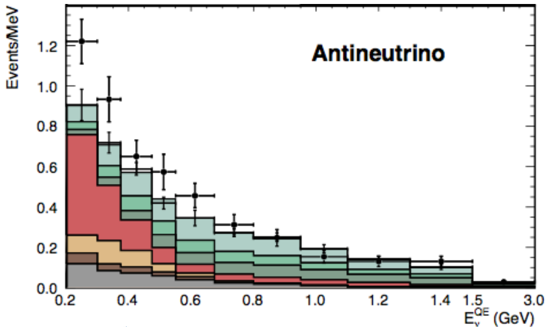




look for an **excess** on top of the expected intrinsic electron neutrino CC rate

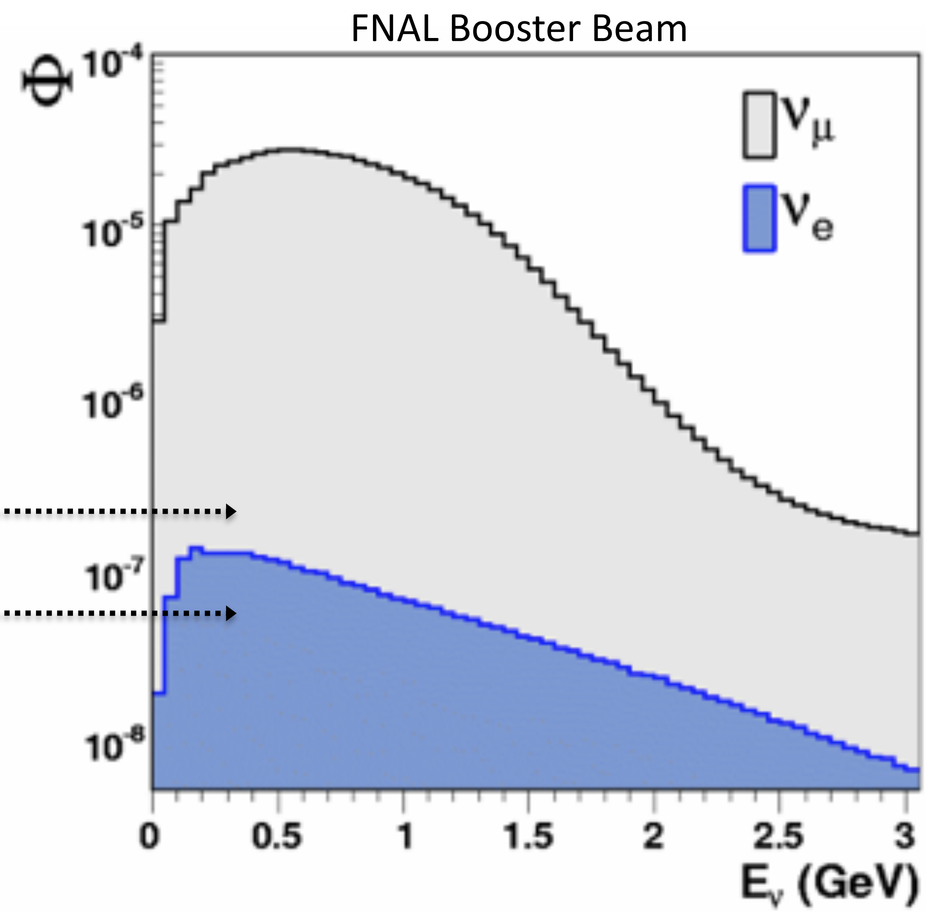
sounds simple enough...

The One Detector Analysis



plus the uncertainty on any non-electron backgrounds

while the (*flux × xsec*) is constrained, the **ID efficiencies** between muon CC events and electron CC events are not strongly correlated, so there remains an energy dependent uncertainty on the observed rate of intrinsic electron neutrinos coming from the **detector response modeling**



Some lessons:

Improve constraint or eliminate non-electron backgrounds

Better understand the electron identification efficiency, or really (flux × cross section × efficiency) for intrinsic electron neutrinos

No one has ever had too many statistics (at least not in antineutrinos)

The experiments:

FNAL BNB Expts.

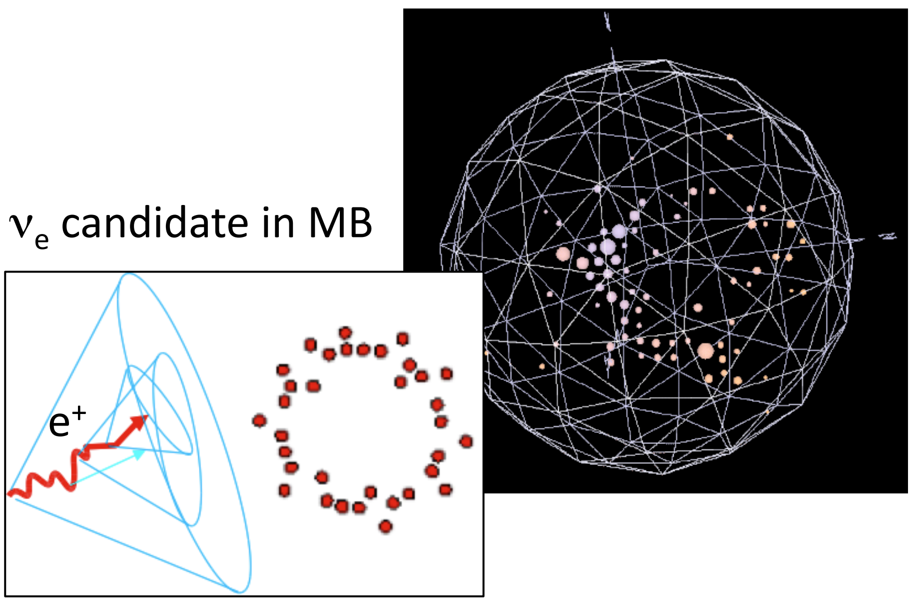
- MicroBooNE – reject NC backgrounds, increase ν_e efficiency
- MiniBooNE+ – reject NC backgrounds
- MiniBooNE-II – constrain ν_e+NC background rates with a near detector
- LAr Near Detector – constrain intrinsic ν_e beam content
- LAr1 – high-statistics far detector measurement of ν_e appearance
- MINOS+ – long-baseline $\nu_\mu(\overline{\nu}_\mu)$ disappearance
- ICARUS/NESSIE – short-baseline two LArTPC detector experiment at CERN


BNB Source
MicroLAr (17ton fiducial)
MicroBooNE (61ton fiducial)
LAr1 (1kton fiducial)
100m
200m
300m
400m
500m
600m
700m
800m
900m
1000m
700m LAr1
541m MiniBooNE, MiniBooNE+
MicroBooNE 470m
200m MiniBooNE-II
100m LAr ND

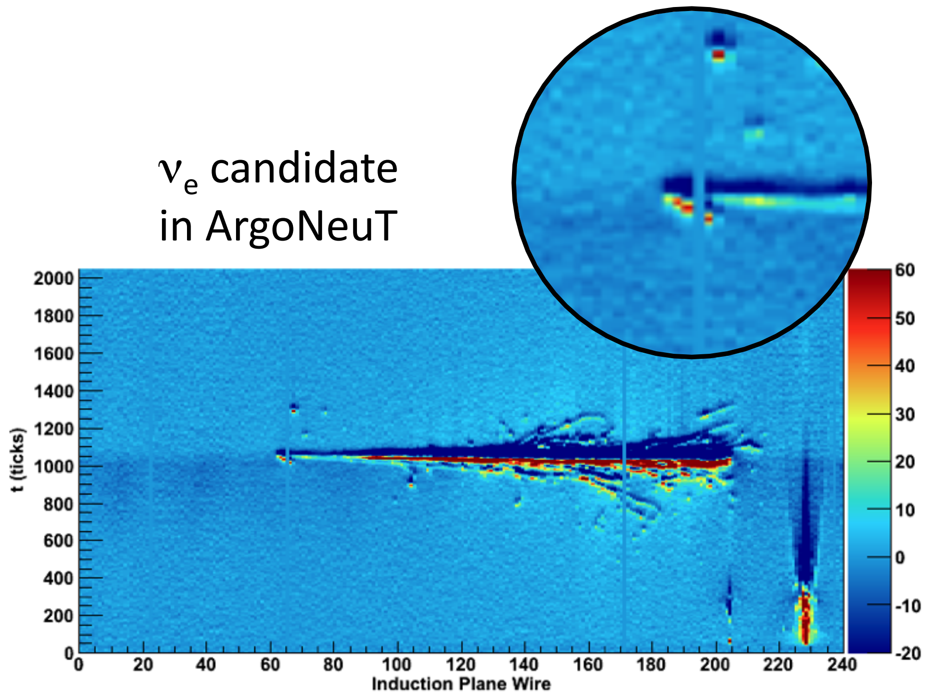
MicroBooNE

- Same L/E as MiniBooNE to address the observed excess
- What does MicroBooNE bring to bear on the question?
  - e/γ in MiniBooNE vs e/γ in MicroBooNE – superior background rejection
  - Also extend to lower electron energies with LArTPC technology

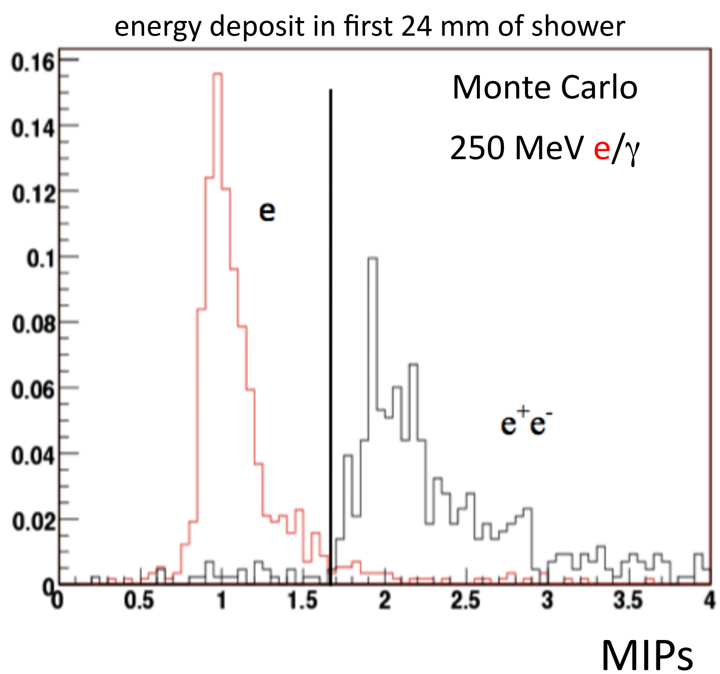
ν_e candidate in MB



ν_e candidate in ArgoNeuT



With 6.6e20 POT of exposure in neutrino mode, MicroBooNE can investigate a critical piece of the puzzle: **are the excess events seen by MiniBooNE electrons or photons?**

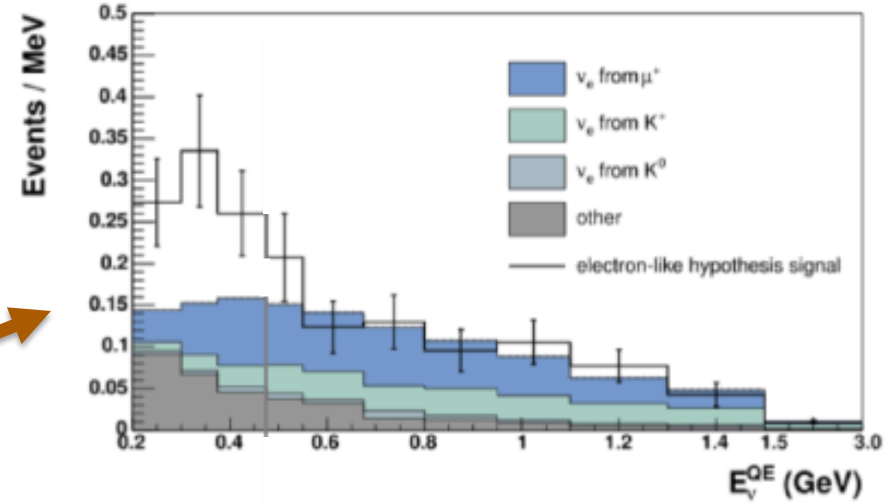


with fine-grained calorimetry of LAr-TPC can separate **electron/photon** showers

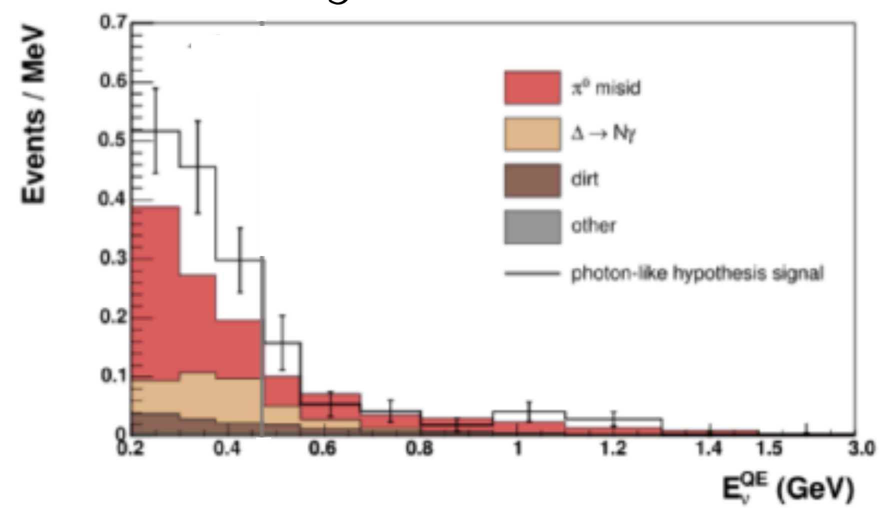
electrons

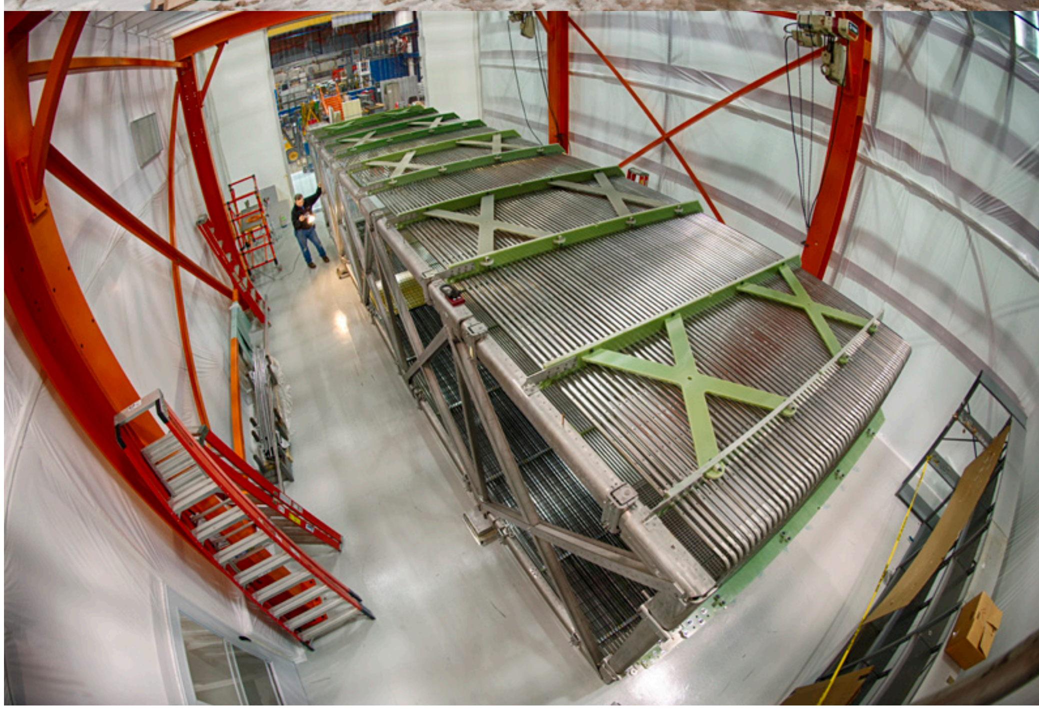
photons

>5σ stat. significance if all electrons



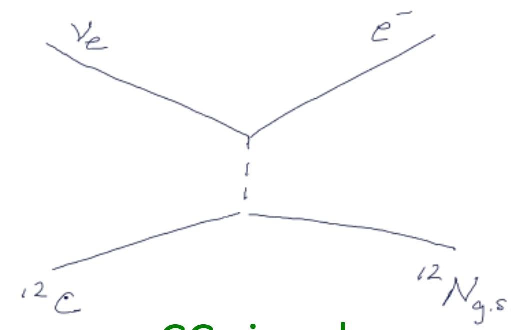
>4σ stat. significance if all photons



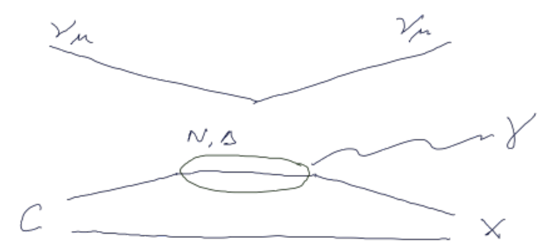


MiniBooNE+

- A proposal for future MiniBooNE running with improved CC/NC separation
  - Add 300 kg of PPO scintillator to mineral oil (~$100k)
    - n-capture (2.2 MeV γ increase from ~6 PMT hits to 20-30 hits)
    - β-decays (~15 MeV better measured)
  - At low energy, if MB excess due to…
    - **oscillation signal (CC)**, then sample of $^{12}N_{gs}$ (β-decay) events with ~0 neutrons
    - **neutral current background**, then no $^{12}N_{gs}$ events but high yield of neutrons (~50%)
    - actual neutron multiplicities constrained with high-stats ν_μ CC and NC samples
  - neutron tagging allows a test of the nature of the MB low-energy excess via CC/NC identification
- Could run concurrently with MicroBooNE



CC signal

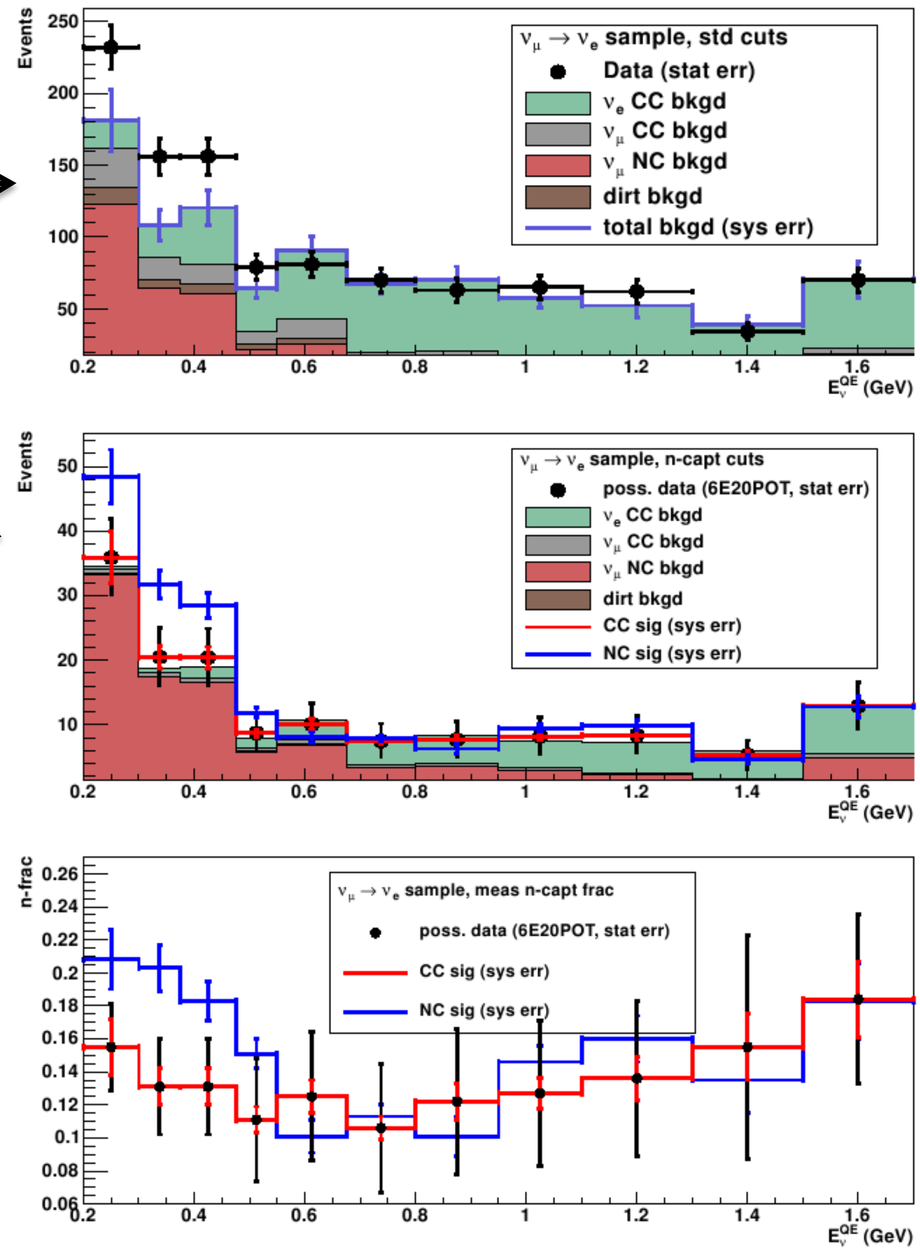


NCγ background

MiniBooNE+

Standard MB ν_e analysis

Add neutron tag



Note most CC events disappear

If excess due to CC interactions (red line), then excess disappears

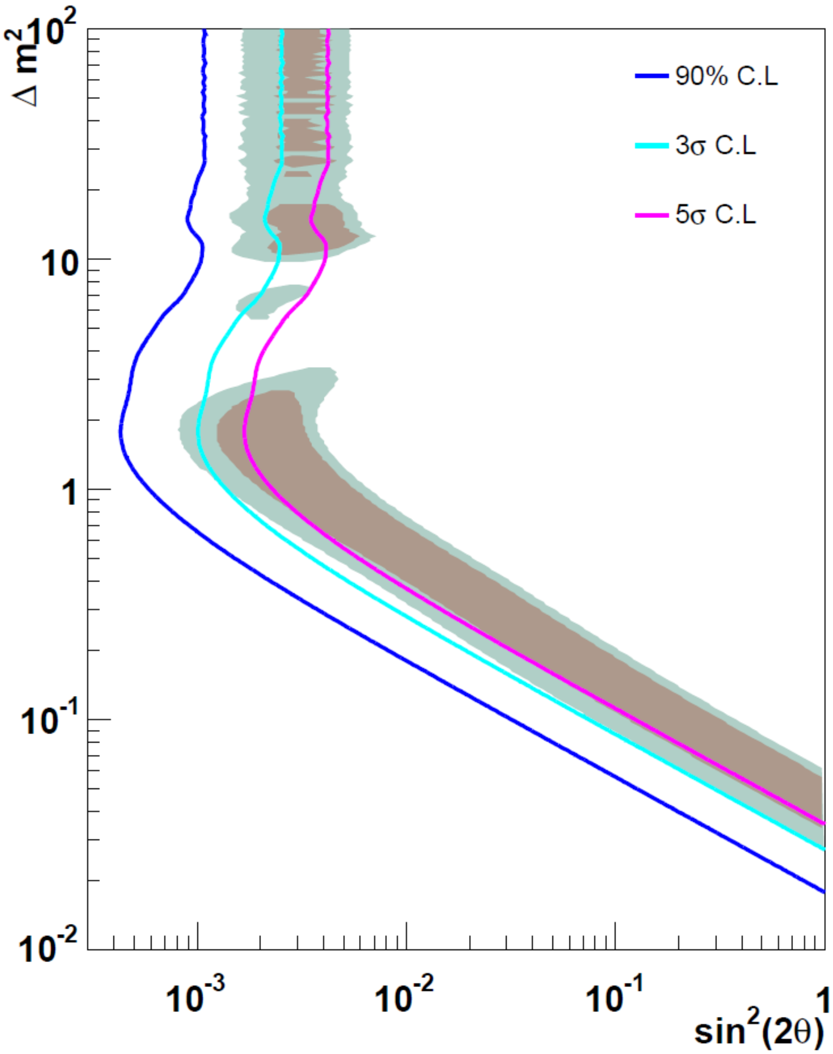
If excess due to NC background (blue line), then excess remains

plots for 6.6e20 pot

MiniBooNE-II

- A proposal to build a near detector for MiniBooNE
  - Construct an identical MiniBooNE detector at ~200 m along the FNAL Booster Neutrino Beam
  - Leverages 10 years of MiniBooNE running, analysis development and operations experience
  - By capitalizing on the MiniBooNE civil engineering and development the project could be completed quickly and inexpensively for ~ $10M (if oil, PMTs, and electronics are reused from MiniBooNE)
  - Systematic uncertainties in MB measurements are significantly constrained by near detector measurement of backgrounds
- Could run concurrently with MicroBooNE

MiniBooNE-II



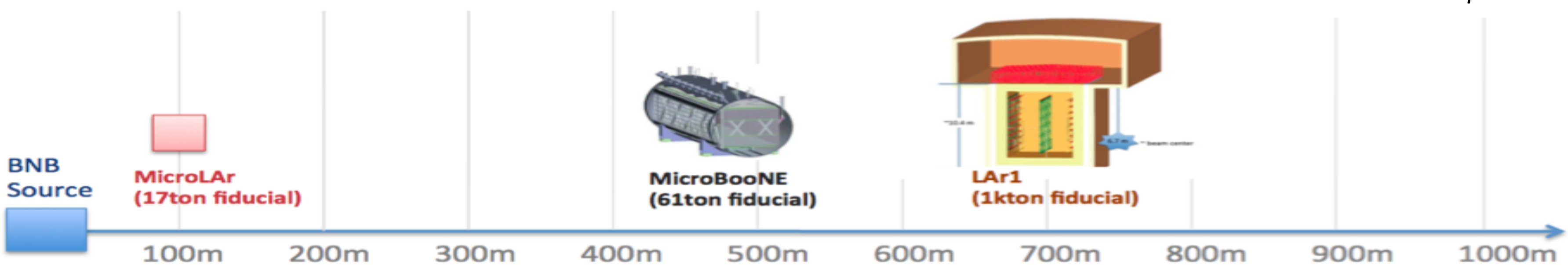
- Sensitivity estimate assuming:
  - Near location at 200 m
  - 1.0 x 10^{20} protons on target in neutrino mode
  - Utilizing full MiniBooNE oscillation sensitivity machinery for systematic error analysis including flux, cross section and detector response

LAr1 - Multiple LArTPCs @ FNAL

- Combine the power of:
  - NC background rejection in LArTPCs
  - A **constraint on the intrinsic ν_e** CC event rate from a ND
  - A **high-stats far detector measurement of ν_e appearance**

Present design is an array of modular units. Could serve as engineering prototype for LBNE far detectors.

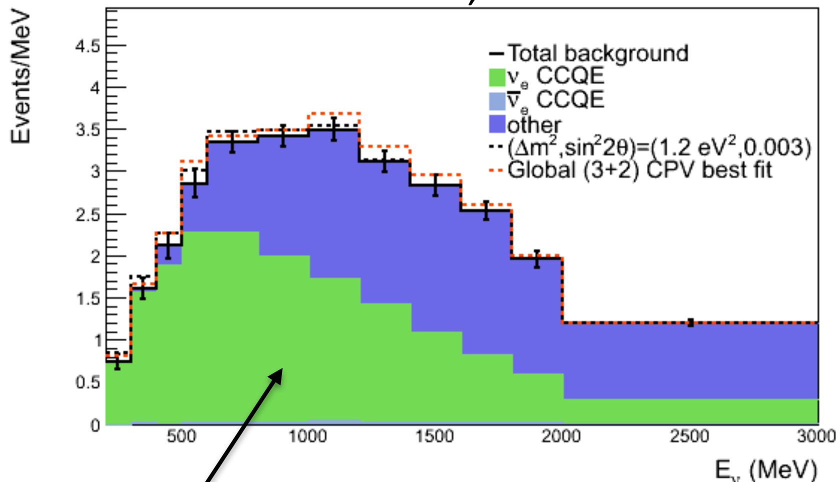
Cost estimate: ~$80M



$$\sigma^2_{stat-100} + \sigma^2_{syst-100} \qquad \sigma^2_{stat-470} + \sigma^2_{syst-470} \qquad \sigma^2_{stat-700} + \sigma^2_{syst-700}$$

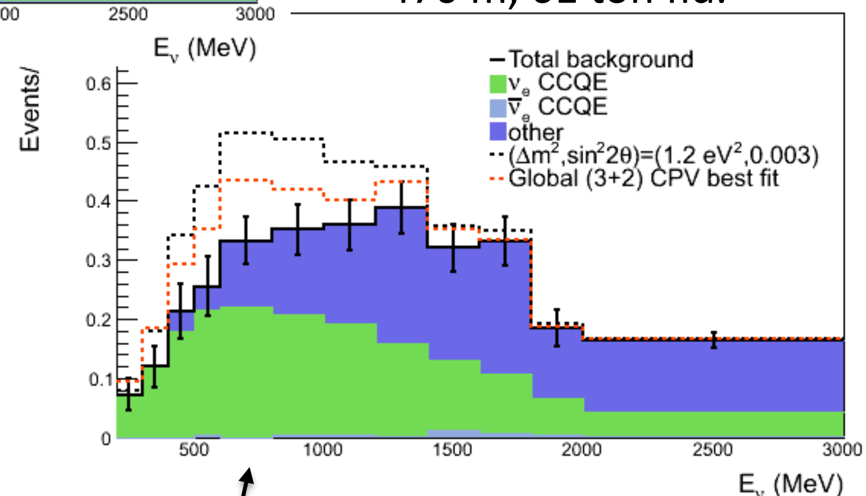
as a first estimate, assume flat 5% systematic uncertainty

100 m, 17 ton fid.

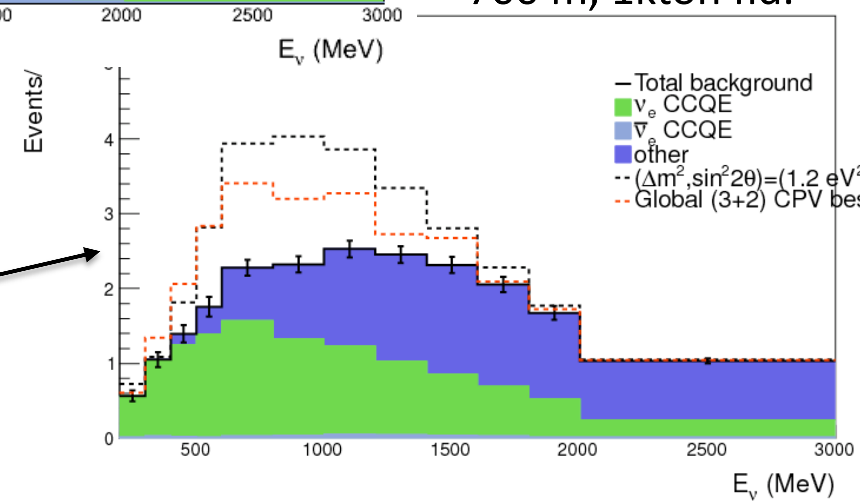


high stats constraint
with very little signal

470 m, 61 ton fid.



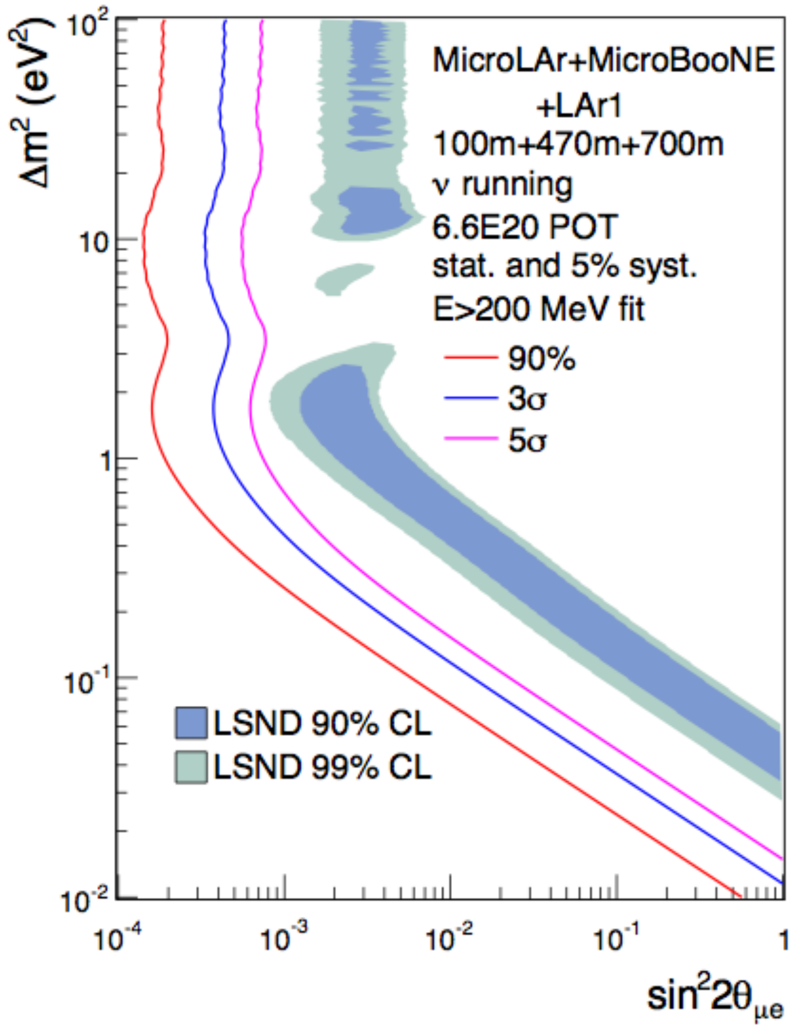
700 m, 1kton fid.



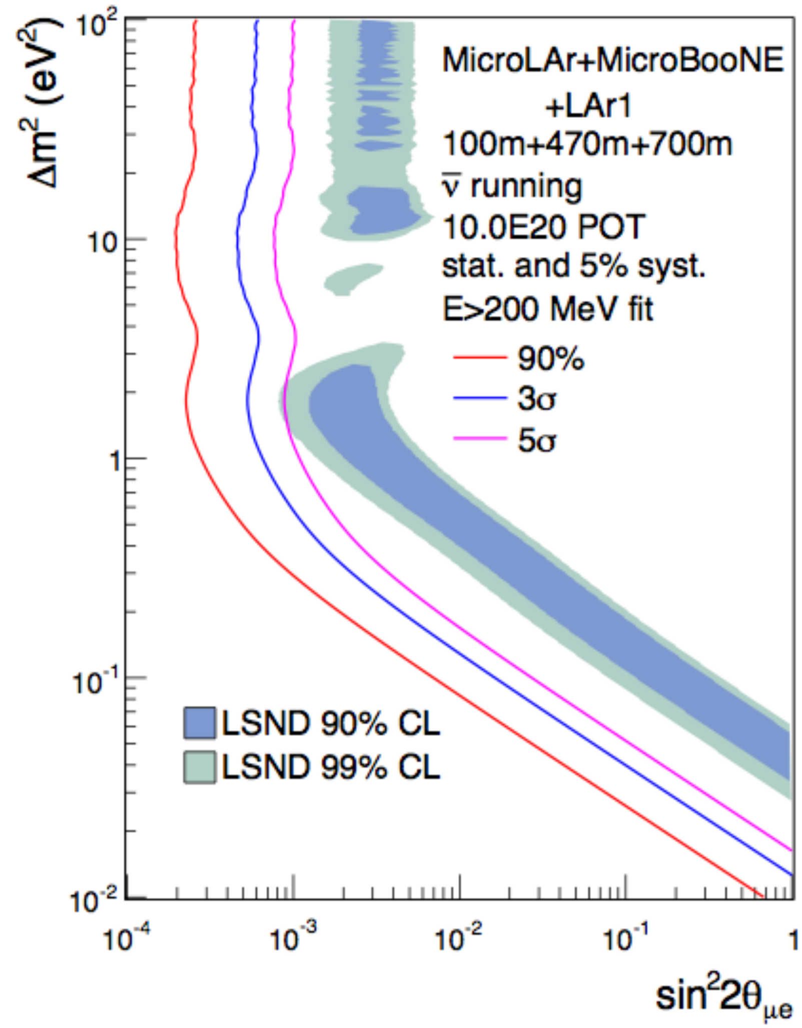
signal measurement
at multiple baselines

LAr1 White Paper

ν

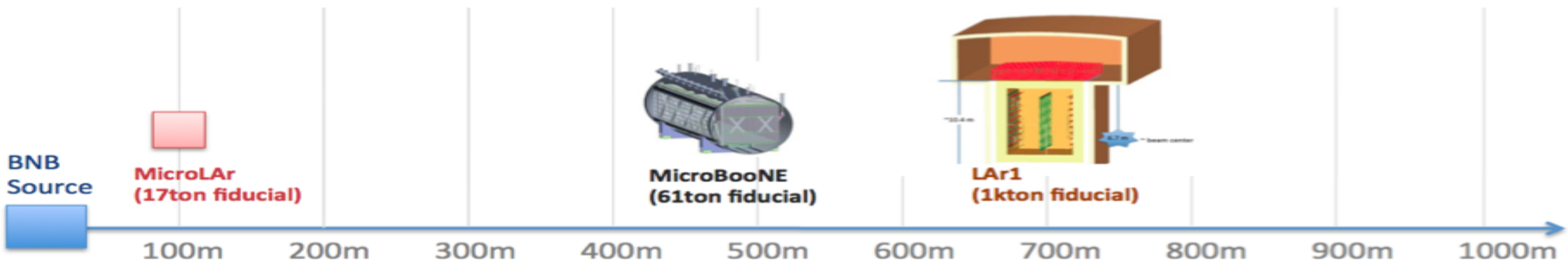


$\bar{\nu}$



LAr1 - Multiple LArTPCs @ FNAL

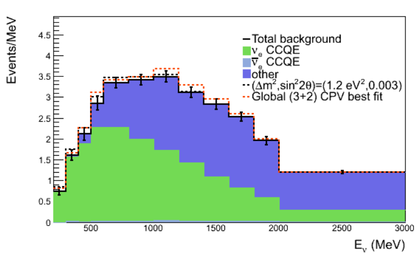
- Statistical errors on the near detector measurement are a limiting case for uncertainty on the predictions at far detectors
  - Spoiled only by imperfect correlations between samples in different detectors
  - LAr1 group working on including realistic estimates of detector correlations

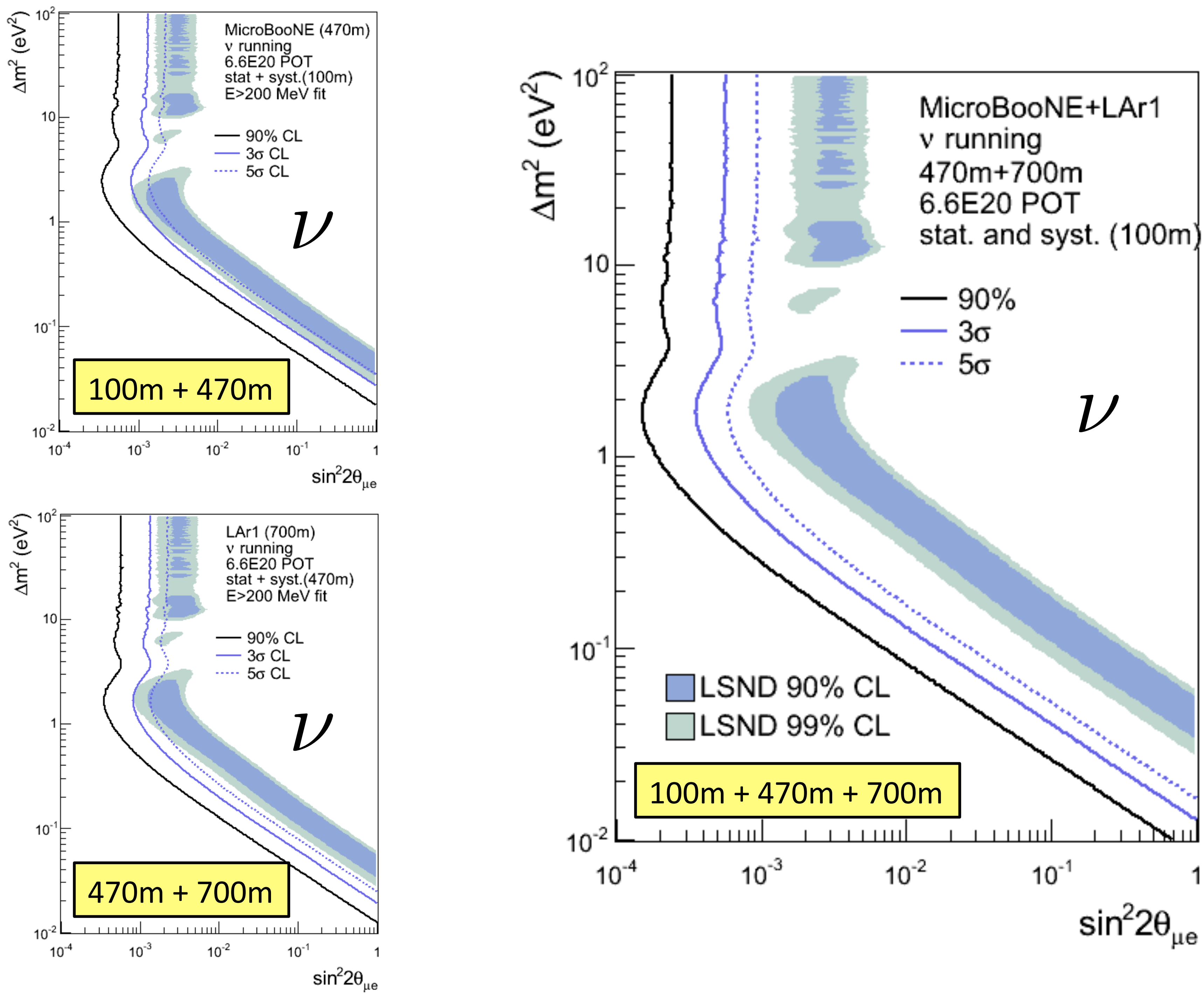


$$\sigma^2_{stat-100}$$

$$\sigma^2_{stat-470} + \sigma^2_{syst-470} \qquad \sigma^2_{stat-700} + \sigma^2_{syst-700}$$

$$\sigma^2_{stat-470} + \sigma^2_{stat-100} \qquad \sigma^2_{stat-700} + \sigma^2_{stat-100}$$

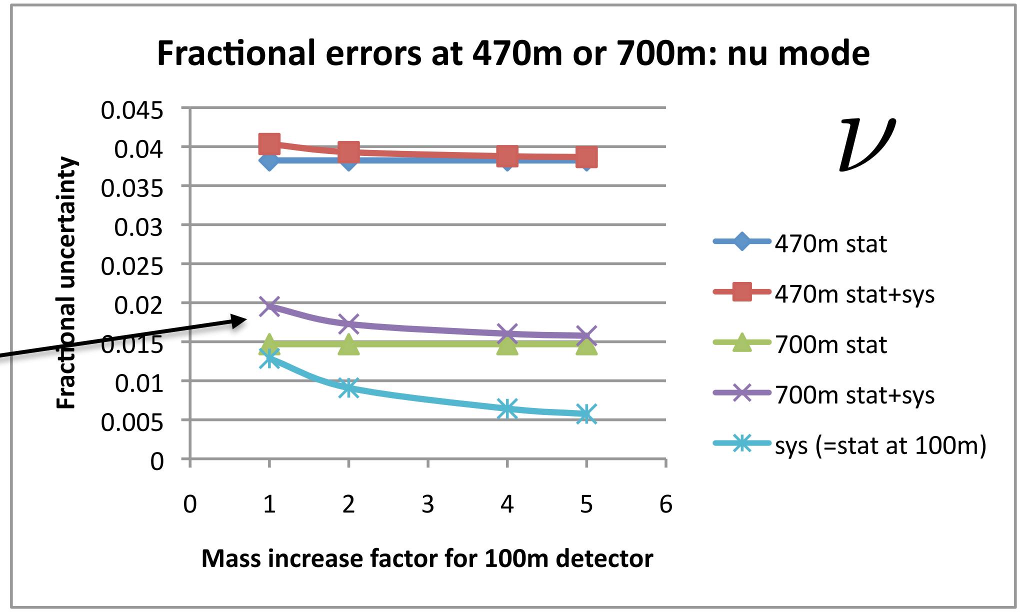




MicroBooNE (470m)
ν running
6.6E20 POT
stat + syst.(100m)
E>200 MeV fit
90% CL
3σ CL
5σ CL
ν
100m + 470m
Δm² (eV²)
sin²2θμe
LAr1 (700m)
ν running
6.6E20 POT
stat + syst.(470m)
E>200 MeV fit
90% CL
3σ CL
5σ CL
ν
470m + 700m
Δm² (eV²)
sin²2θμe
MicroBooNE+LAr1
ν running
470m+700m
6.6E20 POT
stat. and syst. (100m)
90%
3σ
5σ
ν
LSND 90% CL
LSND 99% CL
100m + 470m + 700m
Δm² (eV²)
sin²2θμe

- Optimizing the configuration
(locations and masses)

Impact of increasing the near detector mass (factor x1 = 17 tons)

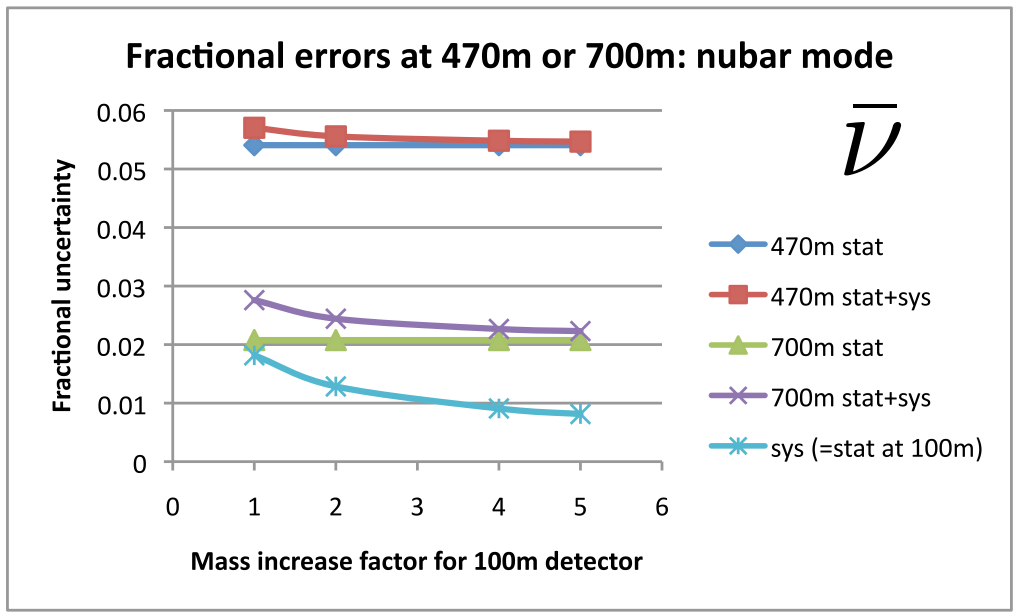


Current estimates indicate competitive sensitivities for a LAr based program at the FNAL BNB

Working to firm them up by time of Snowmass Meeting

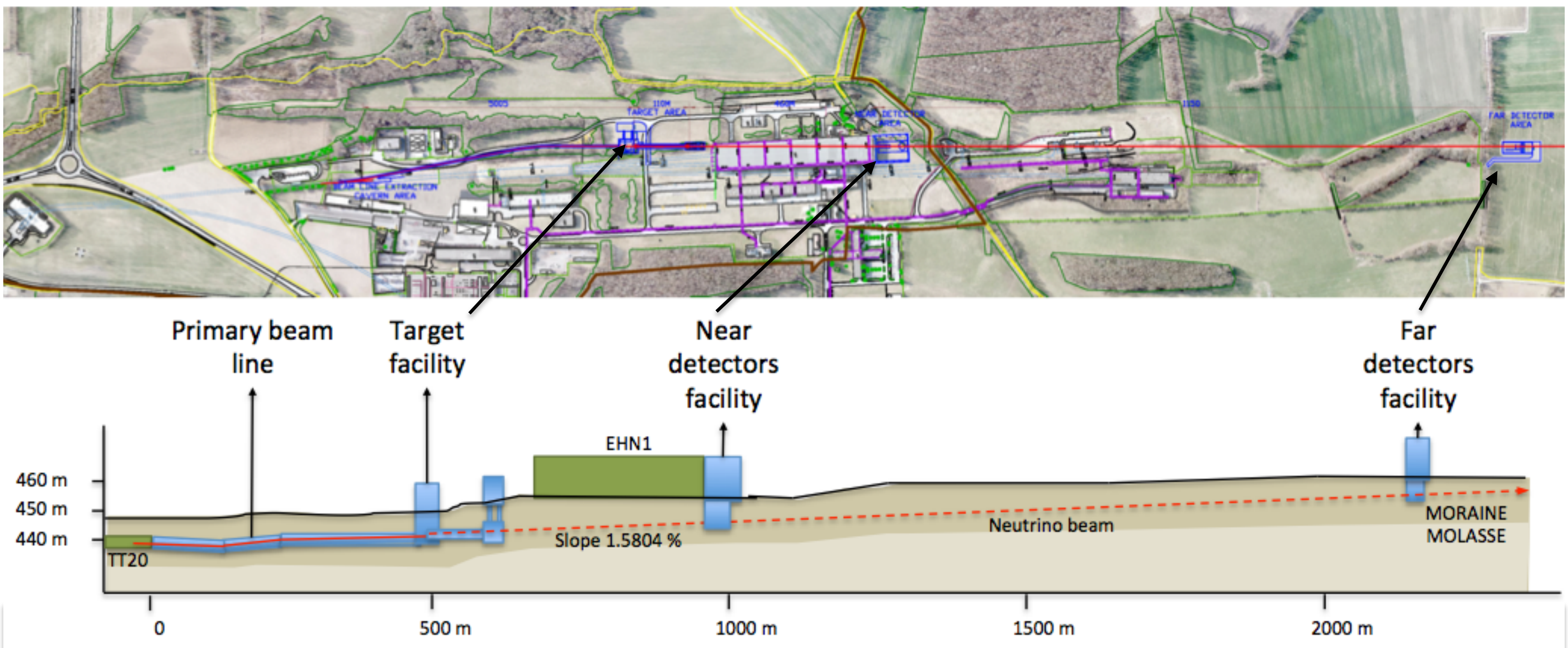
Developing disappearance and NC sensitivities as well

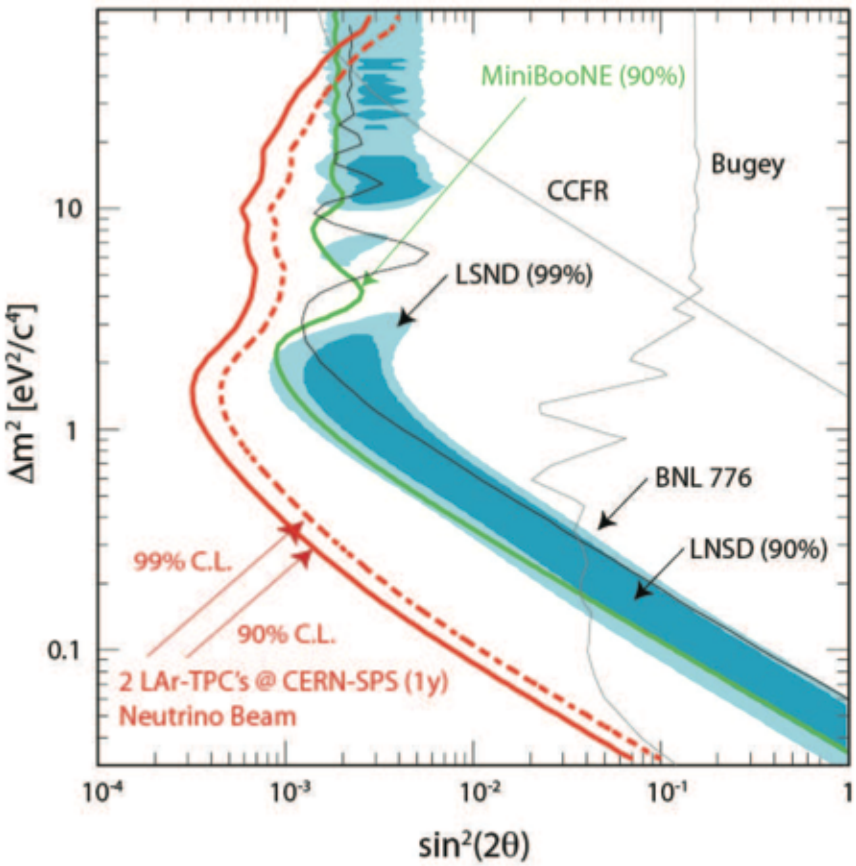
One of the White Papers presents an option to begin early using a new 5-ton LANL R&D TPC as a near detector



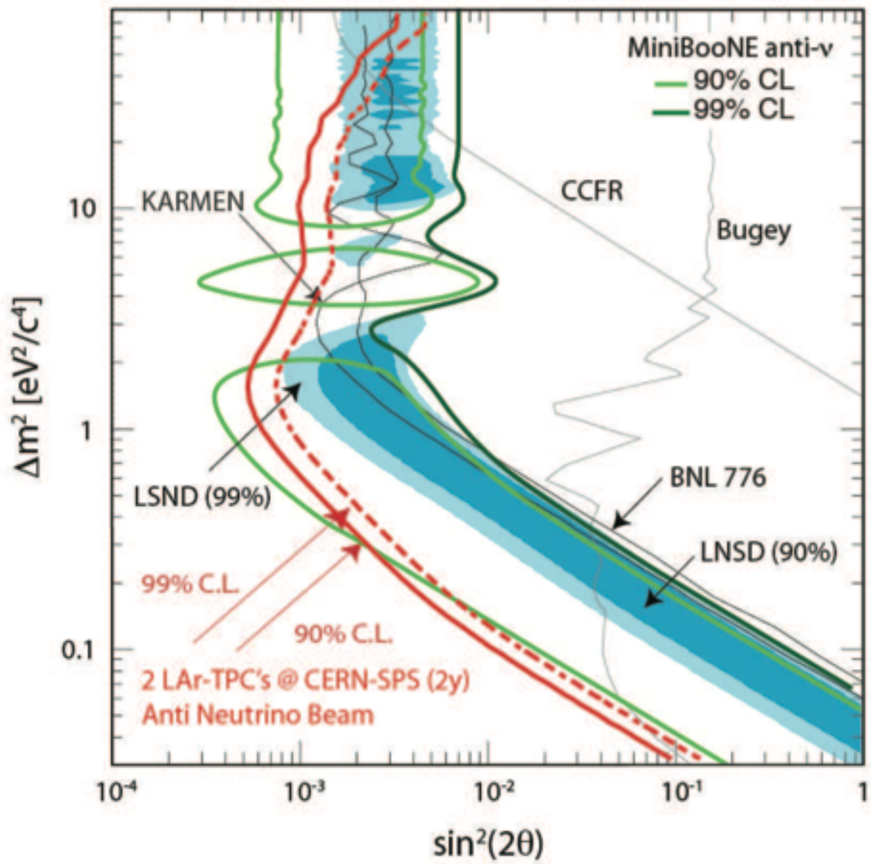
ICARUS/NESSIE @ CERN

- LoI dated February 2013 to build a new CERN Neutrino Facility (CENF)
  - 100 GeV proton beamline at the CERN North Area
  - LArTPC + muon spectrometer at 450m and 1600m locations (reuse of ICARUS T600)
  - See Dave Wark's talk from this morning's plenary session for more details on this proposal and the challenges it entails





4.5×10^{19} pot
neutrino mode



9.0×10^{19} pot
antineutrino mode

from Bill Louis's talk yesterday in Nus Parallel Session:

3+N Models Requires Large ν Disappearance!

In general, $P(\nu_\mu \to \nu_e) < \frac{1}{4} P(\nu_\mu \to \nu_x) P(\nu_e \to \nu_x)$

Reactor Experiments: $P(\nu_e \to \nu_x) \sim 15\%$

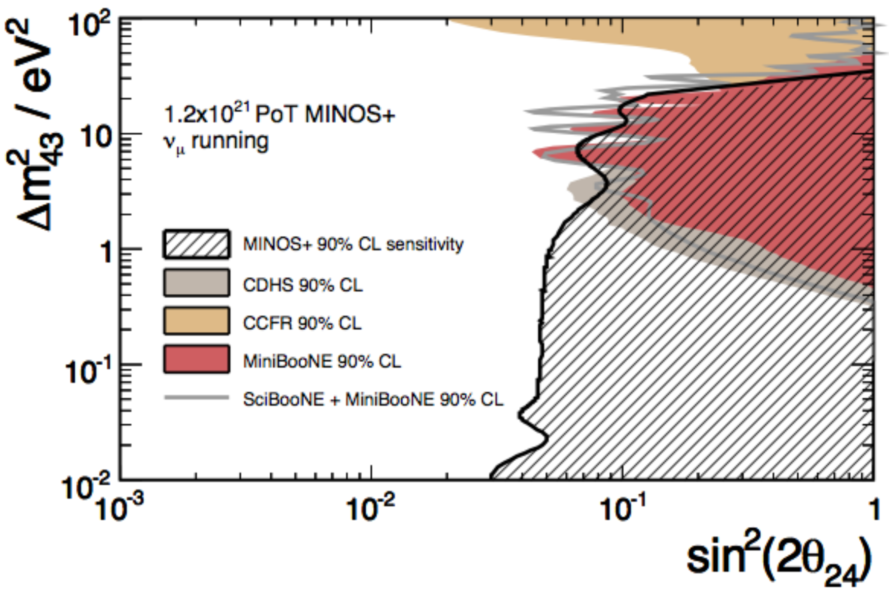
LSND/MiniBooNE: $P(\nu_\mu \to \nu_e) \sim 0.25\%$

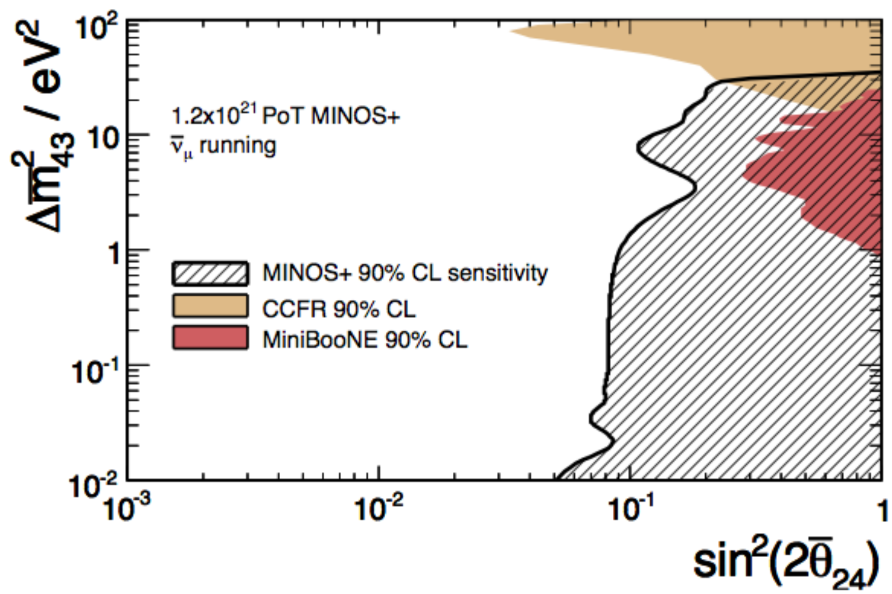
Therefore: **$P(\nu_\mu \to \nu_x) > 7\%$**

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

MINOS+ (a long-baseline DIF expt)

- Continued running of MINOS detector during NOvA higher energy running
- New sensitivity to ν_μ and $\bar{\nu}_\mu$ disappearance, especially at lower Δm^2





Conclusions

- Regardless of one's personal instincts regarding the existing anomalies, we can all presumably agree that a convincing discovery of light sterile neutrinos would be **revolutionary for high energy physics as well as for astrophysics and cosmology**
- A diverse program is necessary to definitively answer this challenging question
- A major new piece of information will be coming within a few years from MicroBooNE (ν_e or NC excess at MB?)
- A continued US short-baseline program would leverage existing infrastructure at Fermilab as well as the expertise developed within the existing short-baseline physics community
- The US neutrino program has an opportunity to play a key role in the resolving of the sterile neutrino puzzle and to potentially make a ground-breaking discovery within the next decade

Backups

1Kton LAr detector

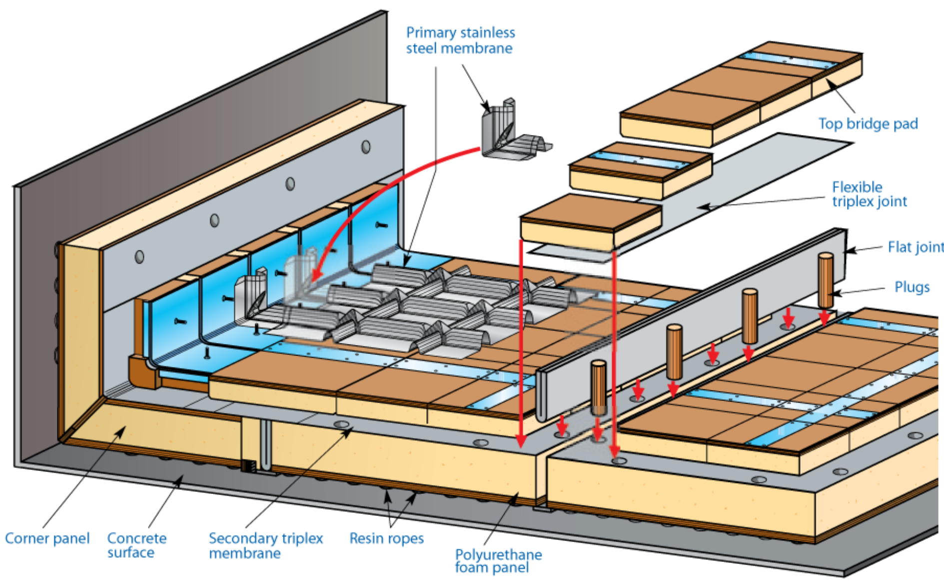
- This 1kton detector will address the anti-neutrino anomalies and serve as an engineering prototype for long baseline program
- The present design is a TPC constructed of an array of modular units:

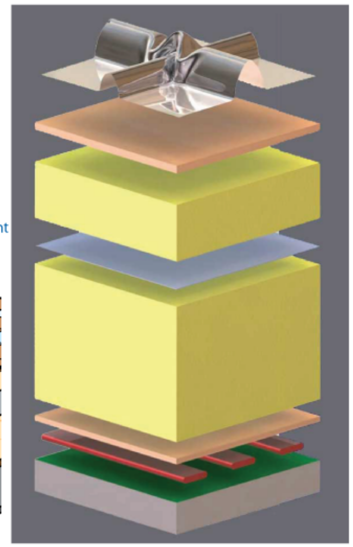
  - Anode Plane Assemblies (APAs 2.5m wide, 7m high and 10cm thick), which contain the wires and scintillation light detection system and instrumented with cold electronics

  - Cathode Plane Assemblies (CPAs 2.5m wide and 7m high), which provide the high voltage electrode to create the drift field

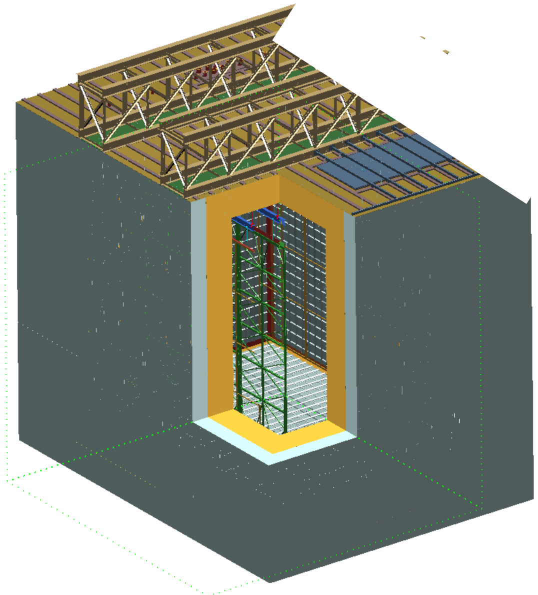
  - Field Cage Panels which shape the uniform electric field of 500 V/cm between the APAs and CPAs

- All the active detector elements are arrayed inside a membrane style cryostat and immersed in ultra-high purity LAr, maintained by the cryogenic system.

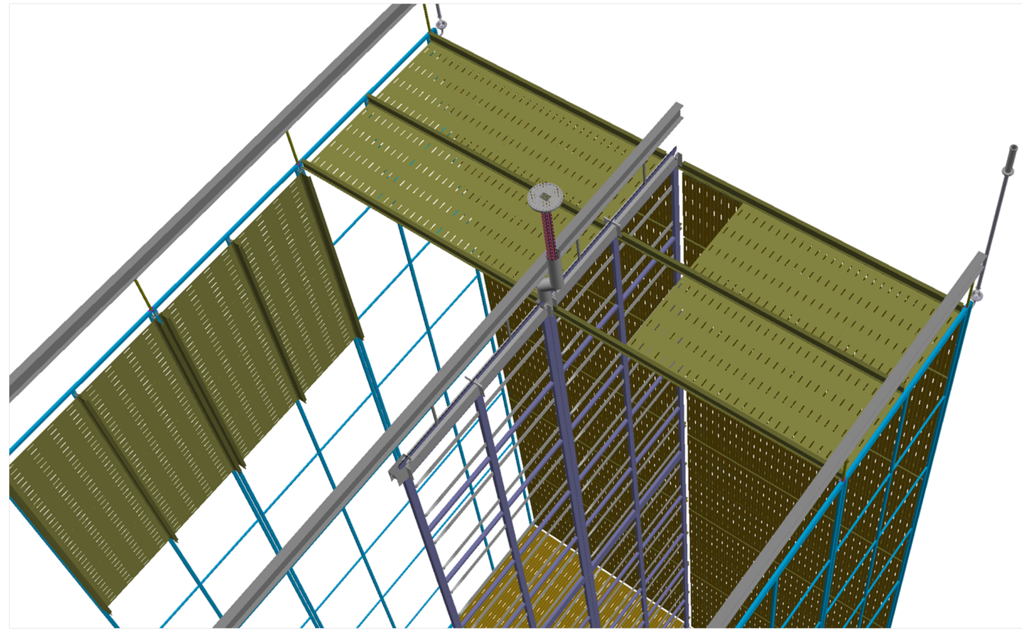




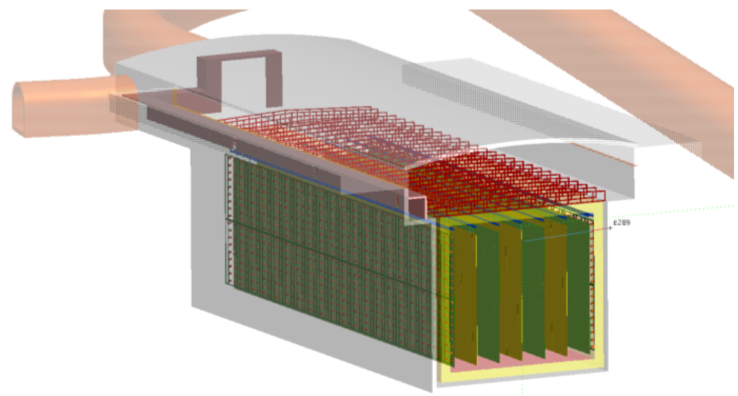
1Kton LAr detector



Membrane cryostat dimensions:
~10m in width, ~11m in height
and ~16m in length



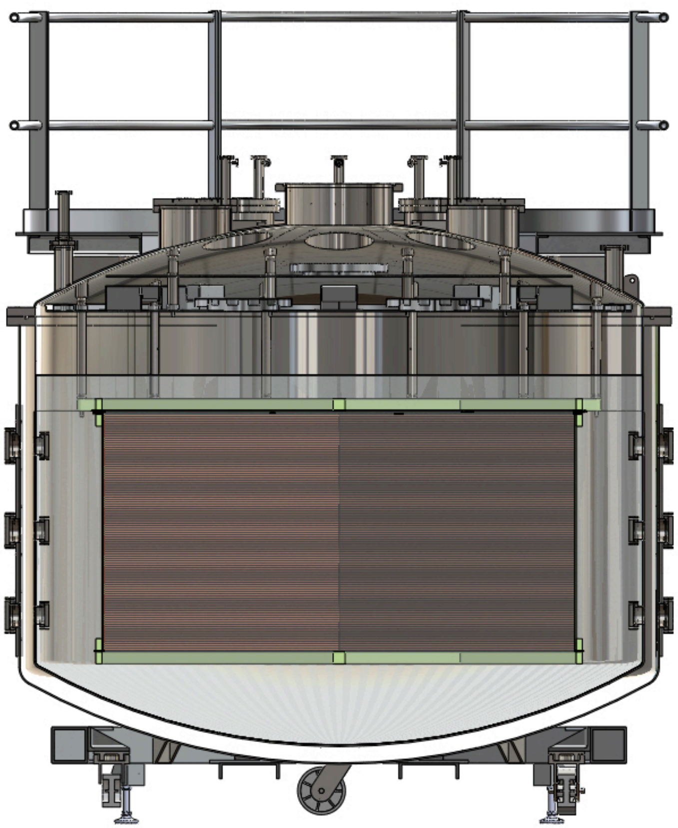
Arrangement of APAs, CPAs, and field cage panels



In addition to the physics program, LAr1 will have a development program serving as the engineering prototype for LArTPCs for long baseline CP Violation Searches (e.g.: LBNE).

LANL R&D TPC

- Proposed to install the former SciBooNE detector hall at 100m in the BNB
- Near detector for MicroBooNE



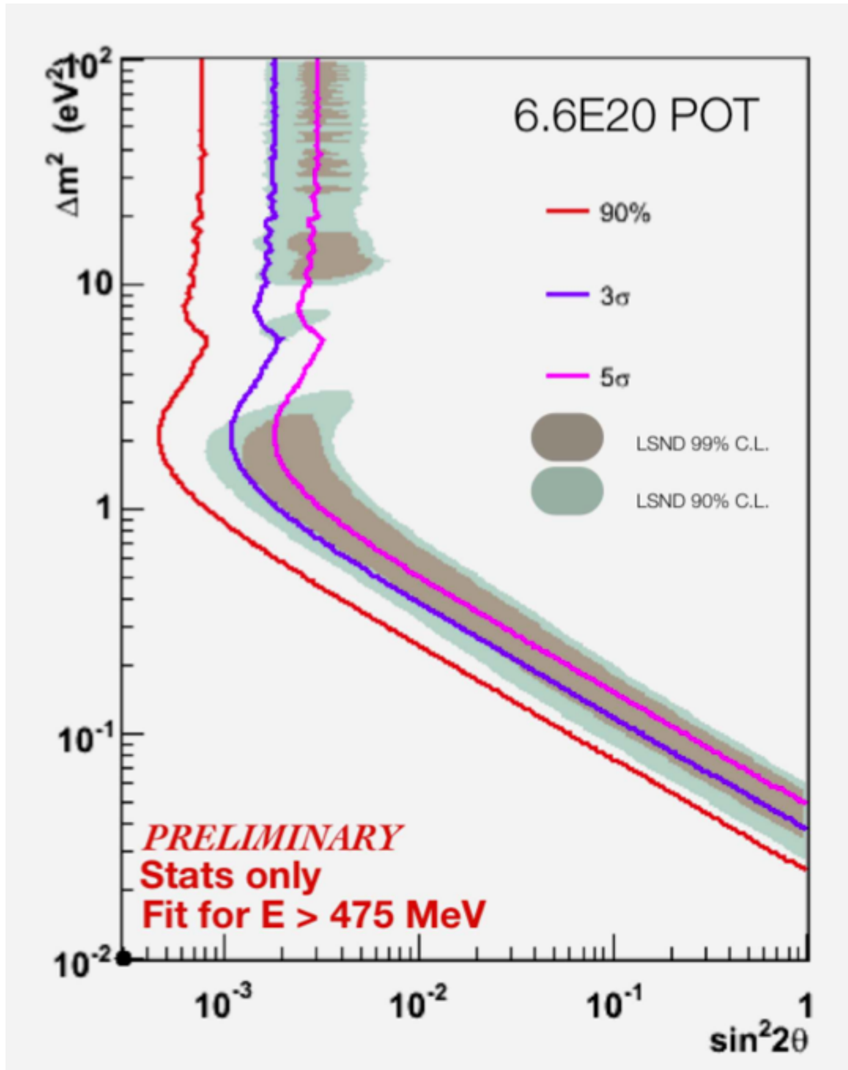
A five ton fiducial mass liquid argon detector is being built at LANL using internal lab funds

The detector is 2m long by 1m high cylinder design with 3mm wire spacing.

Event Type (assume eff= 80% and 6.6E20 POT)	LANL-LAr at 100m, 5ton fiducial mass (events)	MicroBooNE at 470m, 61.4 ton fiducial mass (events)
intinsic ν_e background	576	320
LSND BF oscillations	26	100

	MiniBooNE+	MiniBooNE-II	MicroBooNE	multi-LArTPC @ Booster NB	MINOS+	ICARUS/ NESSIE @ CERN NF
beam power	30 kW	30 kW	30 kW	30 kW	700 kW	100-240 kW
proton energy	8 GeV	8 GeV	8 GeV	8 GeV	120 GeV	100 GeV
peak Enu	600 MeV	600 MeV	600 MeV	600 MeV	5 GeV	2 GeV
Det Location(s)	540 m	200, 540 m	470 m	100, 470, 700 m	735,000 m	450, 1600 m

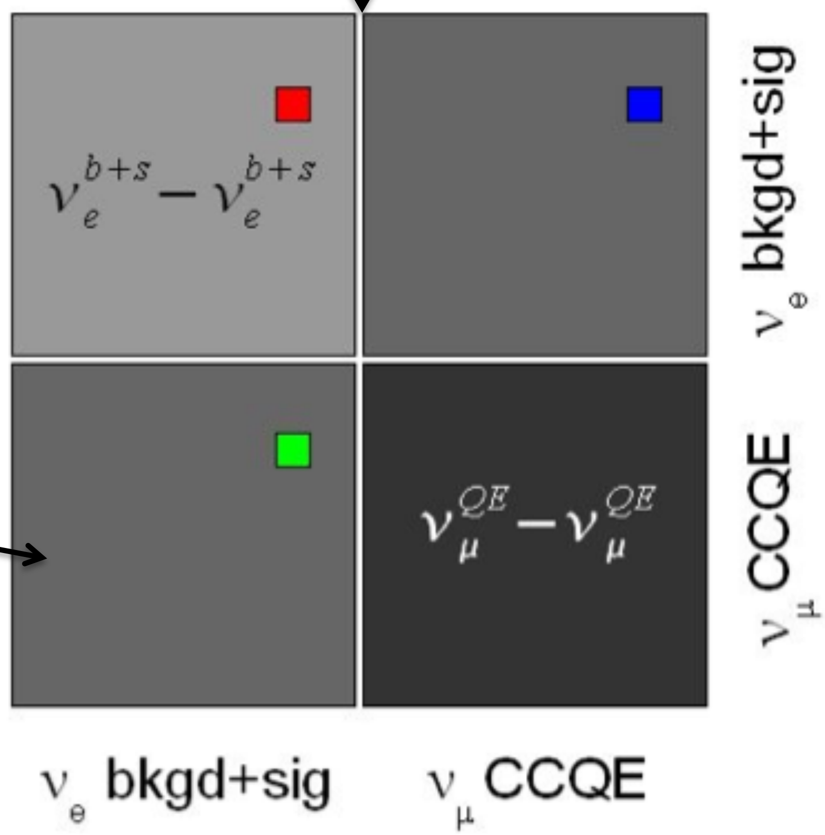
MicroBooNE alone $\nu_\mu \rightarrow \nu_e$ appearance



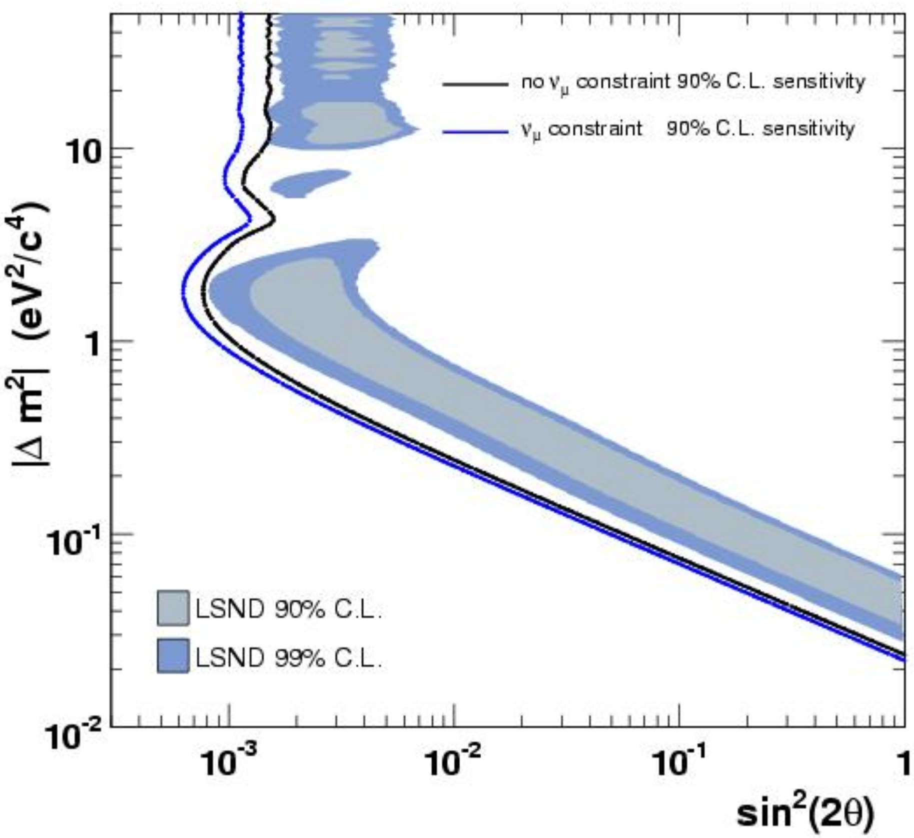
The Combined Fit Approach

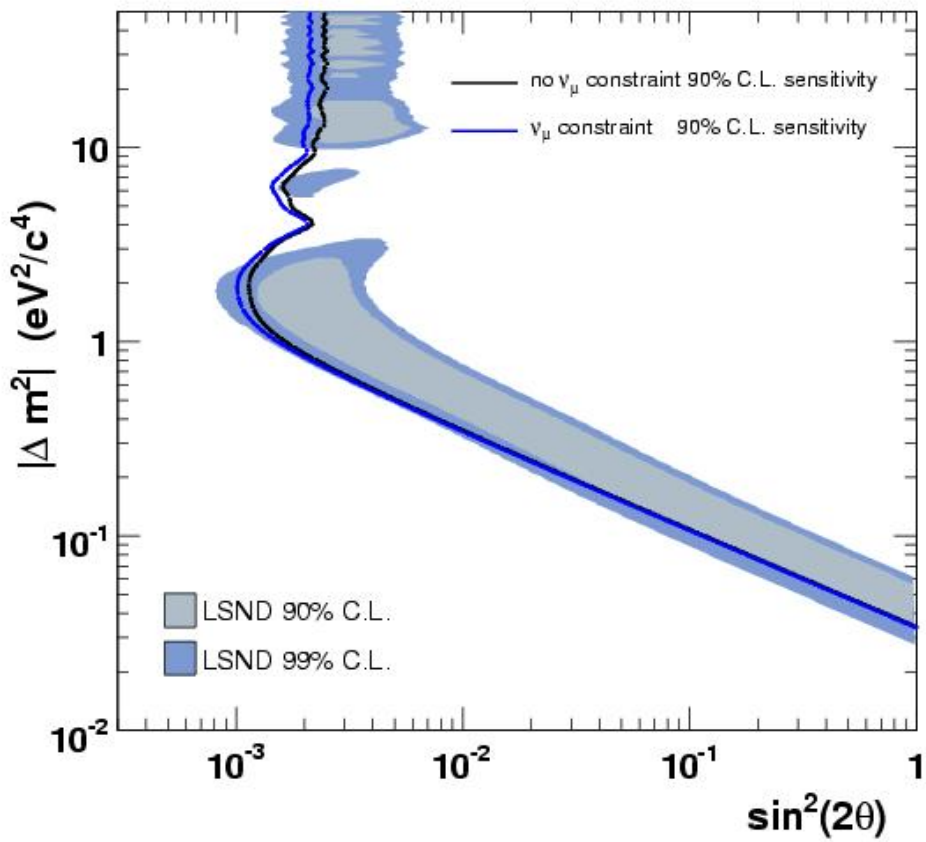
$$\chi^2(\Delta m^2, \sin^2(2\theta)) = \sum_{i,j}^{n_{\nu_e}+n_{\nu_\mu}} \left[\mathrm{N}_i^{\mathrm{obs}} - \mathrm{N}_i^{\mathrm{pred}}(\Delta m^2, \sin^2(2\theta))\right] E_{ij}^{-1} \left[\mathrm{N}_j^{\mathrm{obs}} - \mathrm{N}_j^{\mathrm{pred}}(\Delta m^2, \sin^2(2\theta))\right]$$

the correlations between the high-stats ν_μ sample and ν_e backgrounds are contained here



The Combined Fit Approach



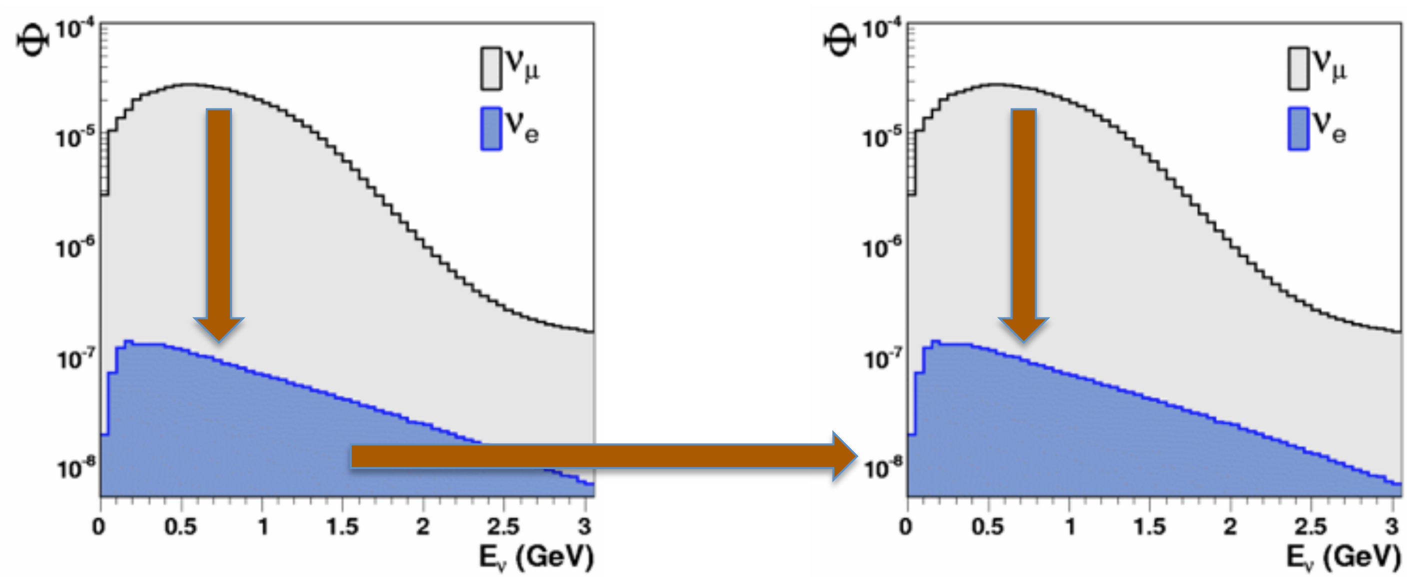


flux and cross section uncertainties only

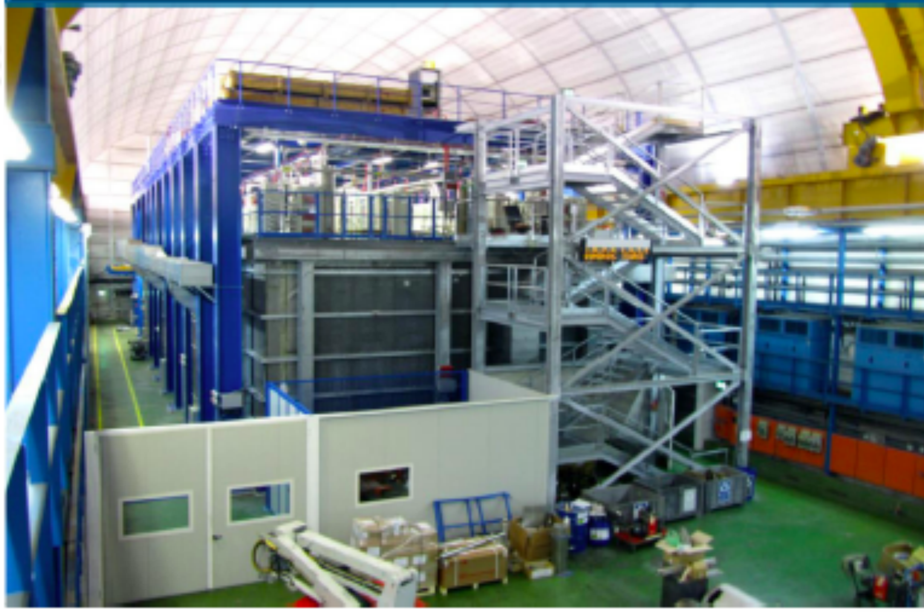
For illustration purposes only. Not a sensitivity for a specific experiment

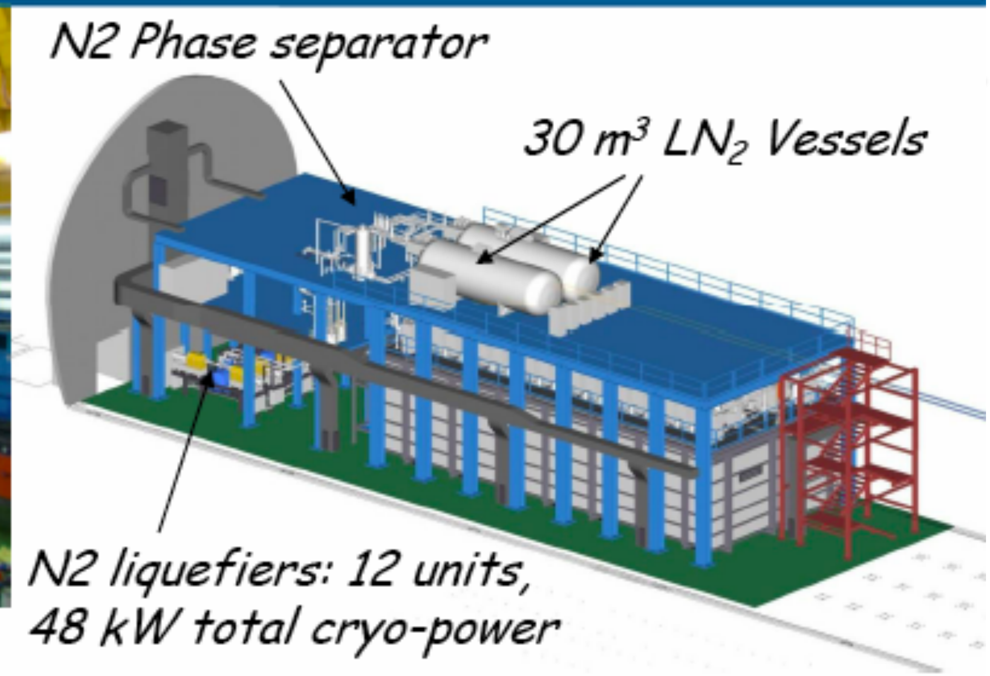
flux and cross section and **detector response** uncertainties

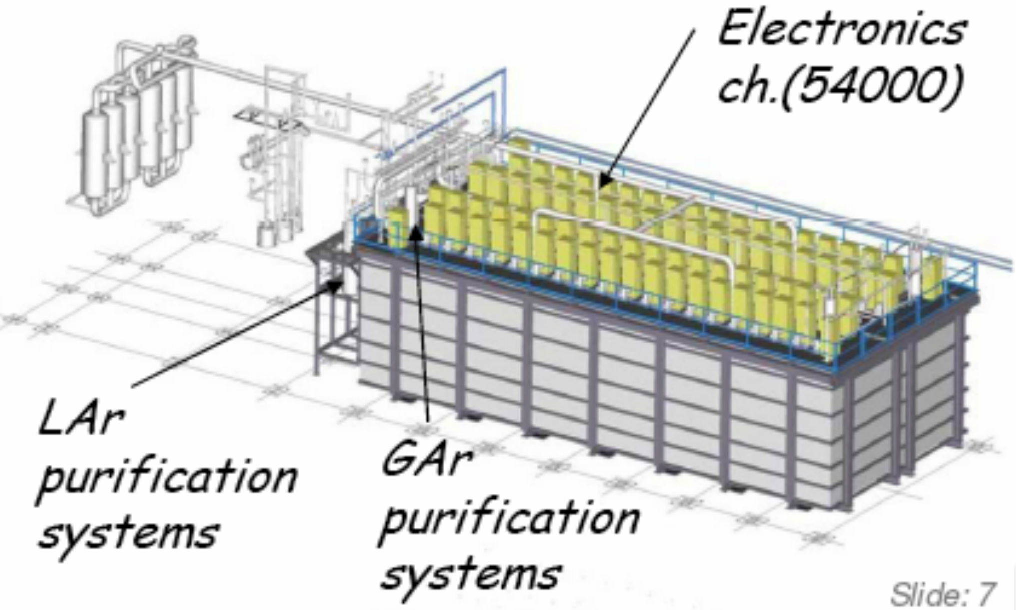
The Multi-Detector Analysis



ICARUS-T600 @ LNGS: 0.77 kton LAr-TPC



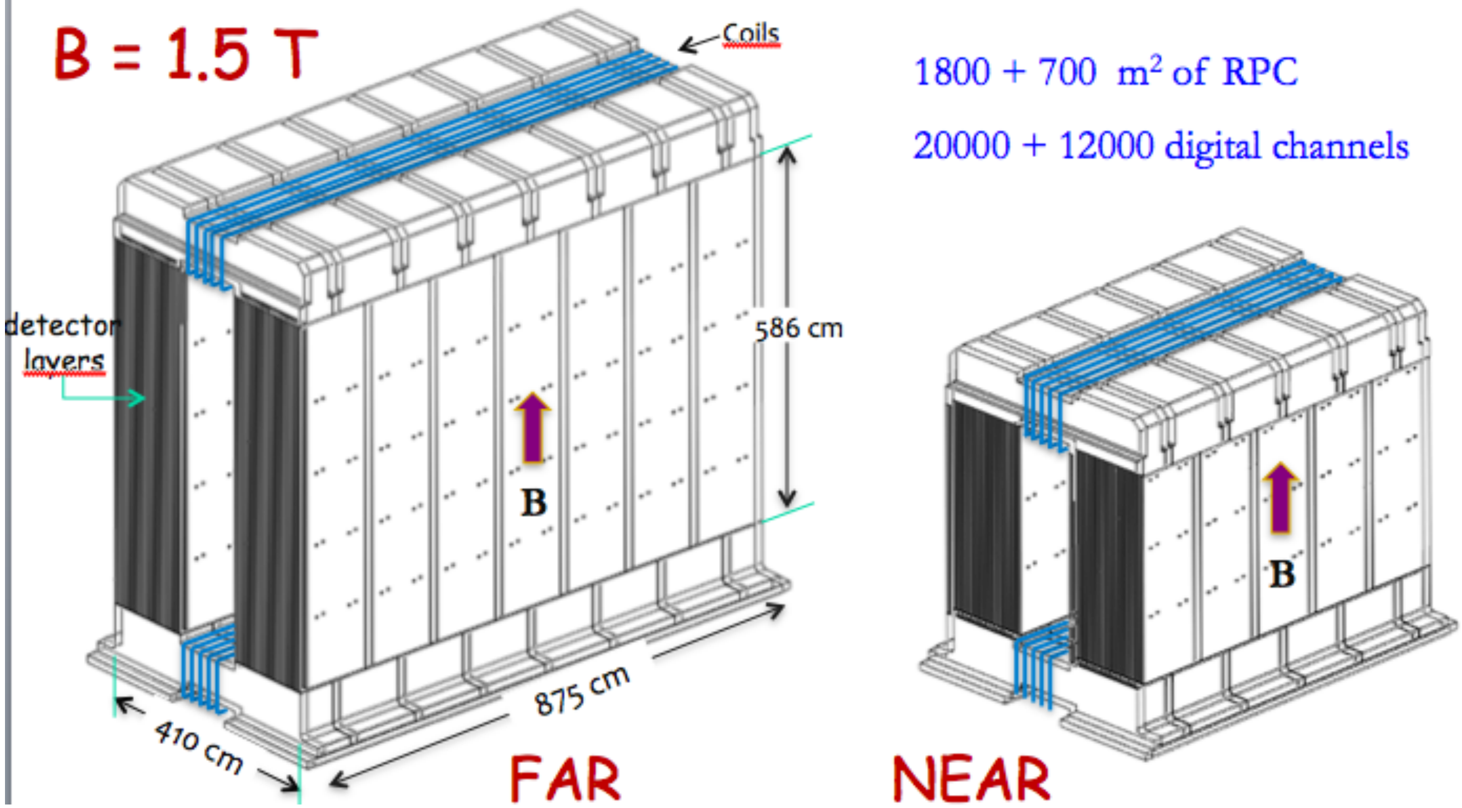




NESSiE iron dipolar magnets

1800 + 700 m^2 of RPC

20000 + 12000 digital channels



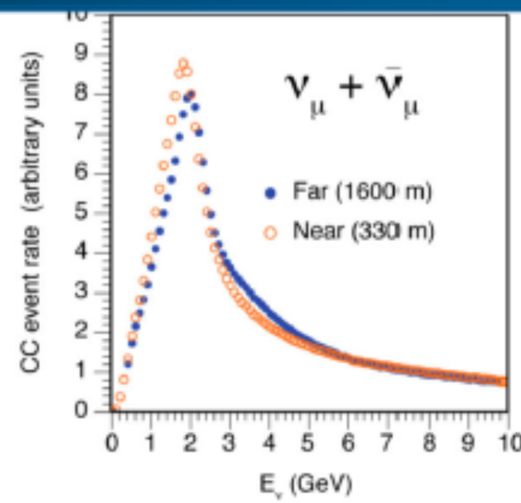
- Exploit the expertise acquired in the design, construction assembling and maintenance of the OPERA spectrometers
- RPC detector with digital read-out
- Same design scheme for the electronics

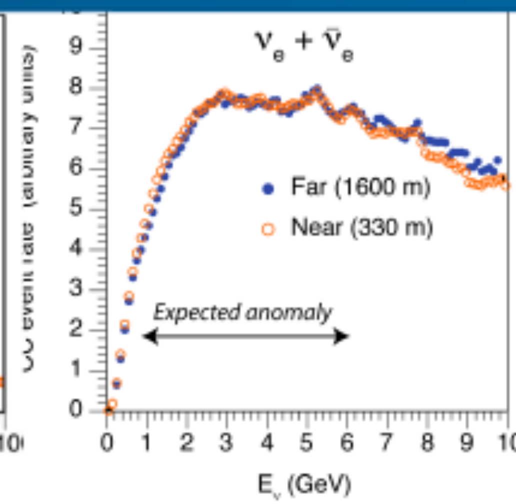
agnetic field with iron slab +

t (muon charge ID+mom. measurement)

Expected signals for LSND/MiniBooNE anomalies

- Event rates for the near and far detectors given for 4.5 10^{19} pot.
- The oscillated signals are clustered below 6 GeV of visible energy





	NEAR (neg. foc.)	NEAR (pos. foc.)	FAR (neg. foc.)	FAR (pos. foc.)
$\nu_e + \bar{\nu}_e$ (LAr)	35 K	54 K	4.2 K	6.4 K
$\nu_\mu + \bar{\nu}_\mu$ (LAr)	2030 K	5250 K	270 K	670 K
$\sin^2(2\theta)=0.02$, $\Delta m^2=0.4$ eV^2	590	1900	360	914
ν_μ (LAr+NESSiE)	230 K	1200 K	21 K	110 K
ν_μ (NESSiE)	1150 K	3600 K	94 K	280 K
$\bar{\nu}_\mu$ (Lar+NESSiE)	370 K	56 K	33 K	6.9 K
$\bar{\nu}_\mu$ (NESSiE)	1100 k	300 K	89 K	22 K
Disapp.. test point	1840	4700	1700	5000

ICARUS/NESSIE ν_μ disappearance

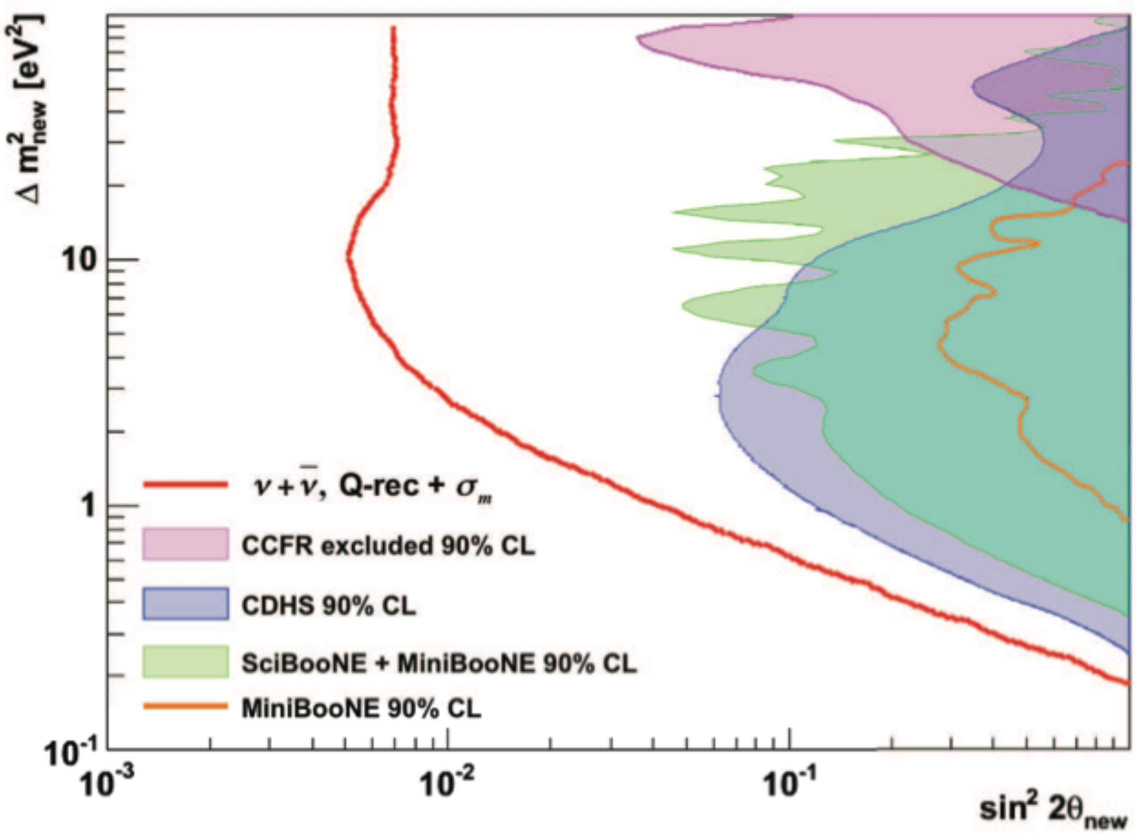


Figure 143. Sensitivity plot (at 90% C.L.) considering 3 years of the CERN-SPS beam (2 years in antineutrino and 1 year in neutrino mode) from CC events fully reconstructed in NESSiE+LAr. Red line: ν_μ exclusion limit. The three filled areas correspond to the present exclusion limits on the ν_μ from CCFR, CDHS and SciBooNE+MiniBooNE experiments (at 90% C.L.). Orange line: recent exclusion limits on ν_μ from MiniBooNE alone measurement.

ICARUS/NESSIE ν_e disappearance